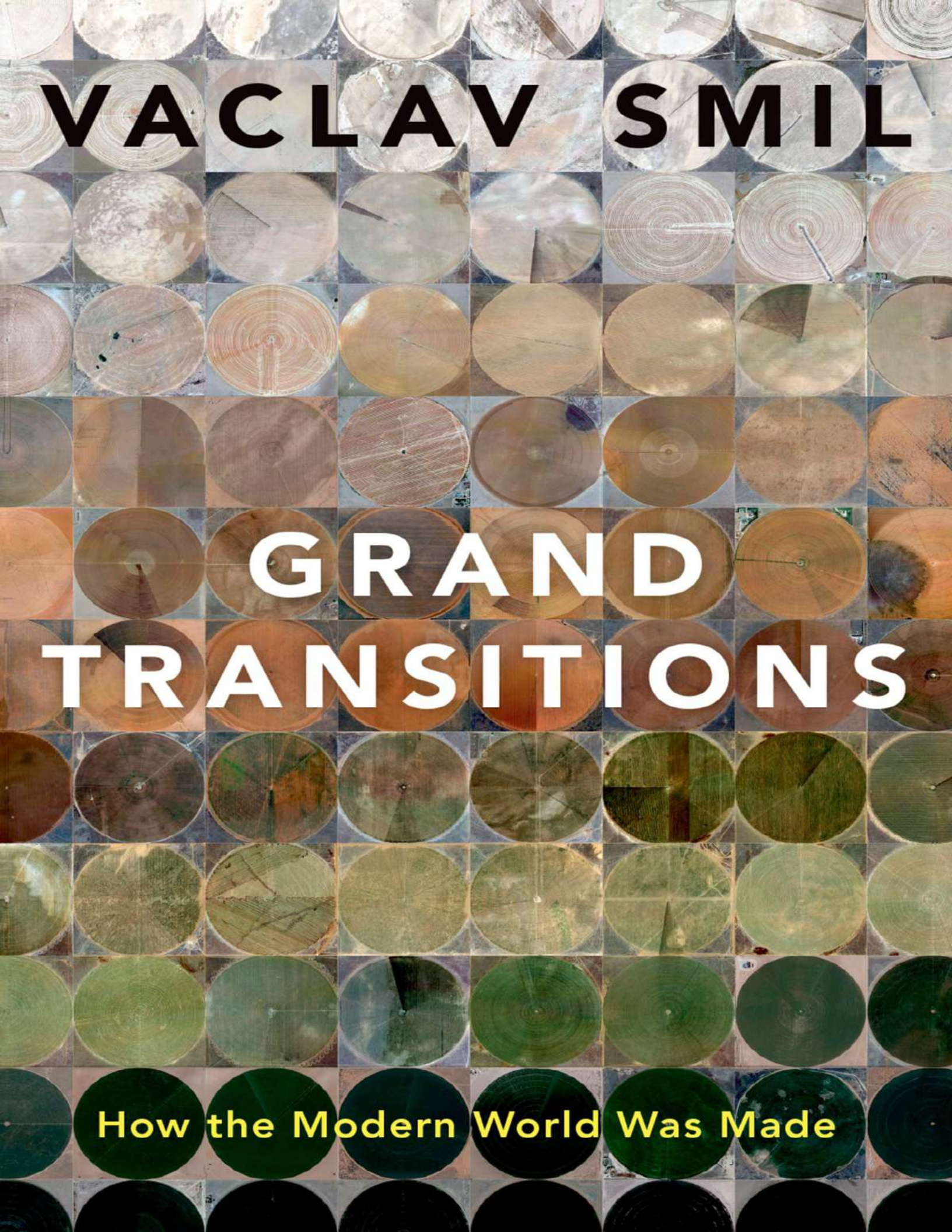




VACLAV SMIL

**GRAND
TRANSITIONS**

How the Modern World Was Made

Grand Transitions

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About This Book

This book is an interdisciplinary inquiry into the five fundamental transitions whose interactions have created the modern world: the eponymous Grand Transitions. My focus is on the history of these transitions in population, agriculture, energy, economies, and environments, and in the following chapters, I look at their (always complex) origins as well as their enabling and multiplying factors. I follow their progress, advances, and diffusion and describe their trajectories, interactions, and consequences.

Writing this book was made easier because of my previous work, specifically that which focuses on long-term transformations of global food production and nutrition (*Energy Analysis in Agriculture, Feeding the World, Harvesting the Biosphere, Should We Eat Meat?*); energy resources and uses (*Energy at the Crossroads, Energy in Nature and Society, Energy Transitions, Energy and Civilization*); key technical and material inputs of modern economies (*Creating the Twentieth Century, Transforming the Twentieth Century, Making the Modern World, Still the Iron Age, Growth*); and the global environment (*Carbon Nitrogen Sulfur, Cycles of Life, Global Ecology*). But, given the present book's scope, the difficulty was in keeping the length within manageable confines while avoiding omissions of critical events, interactions, and outcomes.

This book recounts how we got to this point in human evolution, how the grand transitions brought about today's quotidian realities, which are so far beyond yesterday's imaginations—yet whose benefits are still to reach billions of people in less privileged societies even as the advances we have already achieved imperil the integrity of the biosphere. I do that by focusing not only on precedents, beginnings, and accomplishments but also on detours, cul-de-sacs, and limits. I not only emphasize the key milestones and accomplishments of these grand transitions but also appraise their

uneven progress and consider their emergence and pursuit as a combination of evolutionary process and contingent actions.

But these are more than general, descriptive historical accounts. I take a close look at many specific demographic, nutritional, energetic, economic, and environmental variables, processes, and outcomes, and I do so in unapologetically quantitative ways. This book has too many numbers, but the processes and transformations I examine cannot be properly understood without relentless quantification. In the absence of data, it would be impossible to understand how far we have advanced and how much has yet to be done before the rest of humanity can enjoy the quality of life prevailing in affluent countries—and hence what an unprecedented challenge it will be to increase global prosperity even as we (concurrently) change the energetic basis of modern civilization from fossil fuels to renewable resources.

The interrelated nature of the grand transitions has defined their progress and, given these realities (and also the dominant practices of scientific inquiry during the early 21st century), some readers might expect that I will construct models of these interactions. Such models are now prominent in assessing the risks of climate change, predicting food demand, and charting future energy uses and their composition, and they now provide tools for planning and directing future developments ([Creanza et al. 2017](#)). Models of interactions among population, food, energy, economy, and the environment on the global level began during the late 1960s, with the system dynamics studies of Jay Forrester at MIT ([Forrester 1971](#)), and as an early participant in these efforts I acquired a lifelong skepticism regarding their utility.

I would never question their heuristic value, but their predictive ability remains limited by our incomplete grasp of constituent variables and by our even more uncertain understanding of their complex—and evolving—interactions. Those limitations are why I see every global or universal model and every theoretical explanation primarily as an exercise to be questioned and critically deconstructed rather than as a reflection of reality that might provide useful insights into our futures. Oded [Galor's unified growth theory](#) is an excellent example of this contrast ([Galor 2011a](#)). Constructed by an economist, the theory would seem to provide an excellent framework for explaining the forces behind the grand transitions, and yet it does not contain any explicit recognition of the roles of energy

and the environment in human affairs. As a lifelong student of both of these realms, I find it impossible to understand our world without close attention to energy and the biosphere.

But why then have I decided not to use at least some graphic models? After all, some simple graphing of interactions driving both the specific transitions and those affecting other grand transformations might be the best way to illustrate the web of interdependencies and amplifying or moderating feedbacks. But if such flow charts were to be reasonably realistic—not grossly simplified and hence offering caricatures rather than reflections of the real world—they would be confusingly interwoven and, more importantly, they could not convey counteracting, sequential, and changing feedbacks, and could not capture critical and often much delayed qualitative changes.

When we are trying to disentangle these grand transitions, it is sometimes not even clear what we are dealing with and even when it all began. Was the demographic transition an adjustment shift reacting to changing socioeconomic circumstances, be they falling infant mortalities, rising incomes, or a higher share of women in labor force—or was it an innovation process, with newly available birth-control methods diffusing progressively from early adopters? These paths have not been mutually exclusive and, moreover, their interactions have been shaped by many country-specific characteristics. All of the suggested triggers, causes, and pathways have some merit, if not the same explanatory power. But in any case, it is impossible to offer either an absolute ranking or a neat graphic depiction.

Turning to another complex example, I ask why Britain was the first early modern economy to experience the takeoff of economic growth. What determined its timing? What factors combined to sustain it? What were the respective roles of new energy sources, new scientific knowledge, new technical inventions, and new economic arrangements? Was it really a relatively rapid transformation, justifying the name of Industrial Revolution, or was it a more complex process of gradual economic modernization? The inherent challenges of answering these inquiries are most obviously illustrated by the fact that there has been no agreement about the Industrial Revolution's direct causes or even about the onset and the duration of that transformation.

And from here the complexities become only more knotty, because the uncertain trajectories of many transitions are yet another important argument against imposing generic models. Undoubtedly, the outcomes of some processes could be anticipated in the broadest terms right from the beginning of a transition, and in more specific terms once a transition process is underway. But in most instances, the full import of these transitions—including many unforeseeable realities—is revealed only once they have run most if not all of their course, when new arrangements and new interactions create new realities, open up new capabilities, and result in new (second- and third-order) impacts and consequences.

For example, how does the late stage of the demographic transition affect the advanced state of the food transition? A simple mechanistic view would be that, everything else being equal, countries with reduced fertilities (that resulted in families with a single child) and with an increasingly higher share of childless couples should see lower food consumption per average family. This outcome, in turn, should lower energy use in the requisite agricultural output, and both of these shifts should reduce overall economic output and ease ensuing environmental burdens. But that is exactly what has *not* happened.

Instead we find that the frequency of home cooking declines with decreasing family size, and convenience foods and eating out (or ordering in) become common. Ground meat and many common cuts are convenience foods par excellence, as they can be quickly prepared in fast food outlets or by microwaving. But meat production entails inevitably higher energy inputs, mostly because of the cultivation of feed grains and also because of caring for large numbers of animals in feeding facilities. That livestock must be cleaned, heated or cooled, and supplied with water, with further energy required for the subsequent refrigerated storage and transportation of the meat.

As a result, these unavoidable energy requirements have turned modern meat production into a significant consumer of electricity and fuels. At the same time, higher demand for these energies has also spurred a variety of measures that have resulted in higher conversion efficiencies and relative burdens that have been actually lowered. For example, the overall demand for nitrogenous fertilizers to grow grain has risen, but so has the efficiency of the meat production per unit of feed—that is, per unit of applied nitrogen (resulting in lower nitrogen loss per unit of consumed meat)—while some

previously worrisome emissions were completely eliminated. Perhaps most notably, refrigeration no longer uses chlorofluorocarbons (CFCs), which were implicated in the reduction of stratospheric ozone. But the outlawing of CFCs is also an excellent example how matters can backslide. CFC-11 has been completely banned in China since 2010, but recent investigations found that the chemical is in extensive illegal use as a blowing agent in making polyurethane foam used as rigid thermal insulation (EIA 2018).

As this example shows, influences and feedbacks brought about by a transition can range from straightforward boosts and suppressions to delayed, subtle, and variable feedbacks and even to outright reversals. The quantification of these interactions would show some responses that are prolonged and linear, others involving temporary exponential growth or decline, and still others showing little overall shift in terms of actual inputs or costs but important changes in quality. Hence, any simple flow graphs would be more misleading than revealing.

Consequently, this book will disappoint those who look for simple keys to unlock the origins and mechanisms of grand transitions, those who prefer abstract models to careful recounting of unexpected developments, those who think that markets will take care of everything, and those who expect time-specific forecasts. This announcement is not an excuse, just a reminder: recent decades have seen a flood of publications that rely on formal models and process graphs and use them not only to fit complex realities into narrow confines but also to forecast distant futures (sometimes by citing the third decimal number in global totals). Given that, it might not be too old fashioned to remain unapologetically empirical. That means to forgo modeled generalities, to leave any grand unifying theories to theoretical tomes, and to avoid any overarching explanatory frameworks.

Grand transitions could be seen as just the latest stages of natural selection that are intensified (and perhaps even directed) by the unique cultural, social, and technical capabilities of our species—but that reality has more to do with constraints than with particular (and always highly contingent) outcomes. There has been nothing inevitable about the trajectory of our species. Its evolution could have been derailed or terminated by many events, from a volcanic mega-eruption far larger than the massive Toba event 73,000 years ago ([Williams et al. 2009](#)) to an accidental thermonuclear exchange: there were several close calls during the Cold War decades ([Philips 2020](#)).

And, most definitely, our evolutionary experience does not justify any claims about unstoppable progress to ever-greater capabilities: designating our species as *Homo deus* (Harari 2018) is as unrealistic as is the idea of approaching Singularity (Kurzweil 2017). Our fortunes remain circumscribed by many natural imperatives, and civilization remains vulnerable to catastrophic events, be it the Earth's encounter with a large asteroid or, as the 2020 SARS-CoV-2 pandemic demonstrated, to recurrent viral diseases that in the age of global travel can engulf the planet in a matter of weeks (Bostrom 2008; Smil 2008a; Li et al. 2020).

We have been a remarkably inventive species, repeatedly able to meet a multitude of challenges posed by the waves of concatenated changes engendered by grand transitions. On a personal level, we have not only been able to keep many negative consequences of these shifts tolerably low but have also been able to reduce many of them to marginal rates: risks of transmitting infectious diseases among people living in megacities or the dangers inherent in mass commercial aviation are excellent examples of such achievements. We have been similarly inventive in keeping many environmental impacts of population growth, mass material consumption, industrialization, and urbanization to tolerable levels, but, so far, we have failed in running our economies in ways that would guarantee long-term preservation of the only biosphere we have.

Various forms of pollution can be managed, even eliminated, by expensive but effective technical fixes. In contrast, such degradative processes as the depletion of ancient aquifers or widespread loss of biodiversity have no easy technical solutions. And global warming, the ultimate environmental challenge, arising from the grand population, and from nutritional, energetic, and economic transitions, will require unprecedented levels of worldwide commitments as well as technical and socioeconomic adjustments merely to moderate the most worrisome impacts of higher tropospheric temperatures, the ocean's rise, acidification, and deoxygenation. This challenge may turn out to be beyond our capacity for nimble adjustment: it is now almost certain that we will not be able to limit the increase of average global temperature to less than 1.5°C, the level that is now seen as the maximum compatible with tolerable impacts. Surely no model constructed in 2020 can tell us how we will come out of this by 2050 or 2100. Despite mastering so much we still face the fundamental existential uncertainty.

What I have tried to do throughout the book is this: to explain interconnections and complexities of grand transitions by bringing together findings from spheres of research that rarely speak to one another, while refusing to offer the easy rewards of tidy explanation. I hope that this approach is helpful for understanding our past accomplishments as well as for appreciating the coming challenges.

1

Epochal Transitions

What makes the modern world work? There is no better way to answer this question than by explaining how we got to this point. What has driven the multifaceted modernization process that has created the now quotidian realities of declining fertilities, abundant food, intensive energy use, globalized economy, high mobility, and mass-scale instant communication? Or, how did we get to our postindustrial society beset by environmental degradation of which global warming is only a part? I believe that the most revealing approach to answering these fundamental questions is to view the creation of the modern world as a concatenated series of relatively rapid transitions.

My interest is, once again, historical. My goals are to ascertain diverse origins, complicated processes, synergistic and antagonistic interactions, and complex outcomes of several distinct yet highly interdependent transitions that have always entailed combinations of quantitative and qualitative shifts. These transitions have affected all aspects of civilization as they transformed traditional arrangements into modern societies by changing population dynamics; agricultural practices and food production; choice of energy resources and the scale and efficiency of their conversions; the extent and pace of industrial production and, more recently, of the service sector; intensity of trade; distribution of wealth; and the state of the environment.

The premodern world—with the divide between traditional and early modern societies conventionally set in 1500—witnessed change on many levels, ranging from recurrent violent conflicts (progressing from close fights with edge weapons to powerful artillery), invasions, mass migrations, and empire-building enterprises to admirable advances in technical skills in metallurgy and in arts as diverse as monumental architecture and oil painting, the latter craft advancing from the formally stiff figurative

religiosity of early Byzantine altars to the supple allegorical delights of Botticelli's canvases.

But in the most fundamental, existential terms—in the dynamics of human population growth, in dominant ways of agricultural production and food supply, in securing energy sources and converting them to power economic growth and the generation of wealth—all premodern societies were marked by a high degree of inertia and pattern persistence. Of course, different climates and beliefs and diverse forms of social and economic organization produced many specific outcomes: contrast the highly centralized rule of successive Chinese dynasties with Europe's multitude of mostly small medieval kingdoms defined by constant tensions between the rulers and the aristocracy and between secular and religious powers.

Regions, countries, and nations became distinguished by their cropping systems (single- or double-cropping, intercropping, the presence or absence of major tree crops) and by the numbers and variety of domesticated mammals and birds (more than a dozen species throughout the Old World, only dogs and turkeys in ancient Mesoamerica), diets (ranging from completely vegetarian to highly meaty), and prevalence of specific economic activities (field farming, mixed farming, pastoralism, fishing). Cropping ranged from extensive shifting cultivation to intensive crop rotations helped by elaborate irrigation (characteristic of South China and Southeast Asia).

Everyday diets were distinguished by the consumption, or absence, of dairy products (shunned by all high civilizations of East Asia but consumed by neighboring nomads), meat (whose consumption was prohibited in Japan for more than a millennium until the Meiji emperor himself urged his subjects to eat it), and seafood, and by often complex dietary taboos that were found in almost every traditional culture, not the least in China with its unrestricted omnivory but with many foodstuffs prohibited during illness and pregnancy. Buildings and monuments made of stone or fired brick (characteristic of Europe, the Middle East, and India) contrasted with structures made of wood (dominant in earthquake-prone Japan). But behind even the most impressive manifestations of these differences (Europe's walled cities with cathedrals, the unique fusion of land and water in Aztec Tenochtitlán, East China's dense network of populous towns and villages connected by canals) there were universally shared fundamental commonalities.

There was growth, there was innovation, and there were unmistakable advances, but their scale, extent, frequency, and impact remained scattered and incremental. Quotidian lives of populations were governed by exigencies and subject to limits that would have been perfectly recognizable by people who had lived centuries, even millennia, earlier. Horse riding or horse-drawn vehicles remained the fastest mean of transport on land since the domestication of these large animals by the people of Botai culture (northern Kazakhstan) around 3,500 BCE ([Anthony and Brown 2000](#)) until the introduction of steam-powered trains in the 1820s. Sails served that function on water: their shapes and rigging have seen many changes between the time of predynastic Egypt and the early 19th century, but their use in long-distance shipping began its rapid retreat only with the introduction of steamships during the 1830s.

Highly inertial patterns produced very low population growth, limited food supplies, low-power energy conversions (due to the combination of the low-energy density of wood and its poor conversion efficiency in open fires and simple fireplaces), and barely changing economic performance. Even the most notable national advantages were a matter of degree, not differences of kind. China of the late antiquity under the Han dynasty (206 BCE–220 CE) was more advanced than the Roman republic and the Roman empire in techniques ranging from iron metallurgy to horse harnessing. That superiority endured for some time but the inadequate evidence makes it impossible to decide when it ended. According to [Frank \(1998\)](#) and [Pomeranz \(2000\)](#) China was richer than Western Europe until the end of the 18th century, but according to [Broadberry et al. \(2014\)](#) Chinese living standards peaked by the early 12th century and by 1750 the country's per capita economic product was less than half the British level.

Mothers and Sons

In contrast, new patterns and new norms and expectations created by grand transitions had brought rapid and unprecedented outcomes. In some cases, these shifts progressed so speedily that childhood experiences of an aged person were closer to the lives of her ancestors who died a few centuries earlier than to the lives of her grown-up children, to say nothing about what her grandchildren began to take for granted. Just think of a woman born in a

poor French village in central France during the first decade of the 19th century, when Napoleon was trying to subjugate the continent.

She lived with her parents in a leaky one-room house covered with thatch, drew water from a shallow well, bathed rarely, and shared an old bed with her three siblings. Walking (in wooden clogs) and ox-drawn carts were the only ways for her to get around; her family could not dream about a horse-drawn carriage and, in any case, few people traveled far. Wood and straw were the only fuels to burn, and she had to help her mother gather firewood and carry the heavy bundles home on her back, to glean bits of leftover grain and straw from harvested fields ([Figure 1.1](#)), to feed animals, to cook meals, and to care for younger siblings. There was no inexpensive steel and hence a limited number of durable household metal items, and with limited opportunities for service jobs in the nearby capital all but few of her neighbors were subsistence farmers. And farm work was no idyllic cultivation.



Figure 1.1 The world of the early 19th century: life on farms, long hours of manual work, frugality. Jean-François Millet, *Les glaneuses* (1857). Musée d'Orsay, Paris (RF592).

Manual labor supplemented by animal draft supplied the dominant form of kinetic energy as it had been for millennia, primitive farming implements (mostly wooden) were largely the same as a century or two earlier, and that young woman could have been among those seen by James Cobbett (during his 1823 travels in her part of France) who were carrying dung “upon their backs in baskets into the fields . . . and spreading dung with their hands” (Cobbett 1824, 111). I cannot think of a more apposite image: as recently as the early decades of the 19th century the existential foundations of a great European nation (feeding of the post-Napoleonic Bourbon France) rested on manual spreading of dung!

Then think of her son in the Paris of the 1870s, a self-made businessman, a man who could have been walking under an umbrella in Gustave Caillebotte’s *Rue de Paris, temps de pluie* (Figure 1.2), or who could have been one of the protagonists whose social rise was so vividly portrayed by

Émile Zola in his Rougeon-Macquart cycle of 20 *romans* (published between 1871 and 1893), which, I would argue, is perhaps the greatest novelistic summation of early stages of several rapid transitions to modernity during the Second French Empire (1852–1871).



Figure 1.2 The world of the late 19th century: new cities, new affluence, new aspirations. Gustave Caillebotte, *Rue de Paris, temps de pluie* (1877). The Art Institute of Chicago. Charles H. and Mary F. S. Worcester Collection, 1964.336.

Benefiting from these fast changes, the son of a manure–hand-spreading mother lived in a spacious apartment in a multistory building on one of the broad new boulevards that were carved by George-Eugène Haussmann’s bold reconstruction from the decrepit houses and narrow streets of the old city ([Figure 1.3](#)). He spent weekends at his suburban cottage, where he kept improving his garden or sailing on the Seine in a small boat. And during the first decade of the 20th century, his son lived in an apartment lit by electricity and heated by town gas made from coal; rode electric streetcars

and the Métro's expanding lines (and was thinking about buying a car); and in summer he vacationed in Étretat on the Normandy coast, or on the Riviera. His grandmother's Napoleonic-era life was not much different from the lives of her ancestors living even three centuries earlier—while his life was far closer to our everyday urban experiences.



Figure 1.3 More than a century later: cars instead of horse-drawn carriages, otherwise the urban environment endures. Camille Pissarro, *Place du Théâtre Français, Paris: Plui* (1898). Minneapolis Institute of Art, The William Hood Dunwoody Fund.

And China offers an even more extreme example of grand transitions encompassed by lives of just two generations. A girl born to a poor peasant family in Anhui in 1945, four years before the establishment of the Communist rule, grew up in a society whose mores and material possessions were near carbon copies of life a century ago, with villagers having just enough food to lead stunted and precarious lives. By 1961

(miracles happen) she became the only member of her extended family who survived the world's most devastating famine, between 1959 and 1961: Anhui was particularly hard hit, with many villages losing large shares of their population (Zhao and Reimondos 2012). She married, and her son, born in 1965, came of age in incomparably more promising circumstances. Mao Zedong, the famine's creator, died in 1976 and by the time the adolescent boy's mathematical aptitude opened the door to a high school, Deng Xiaoping had begun his economic reforms.

When the son was 19, food rationing was abolished and he graduated from a Beijing university in 1989. That was the year of great political ferment, when it just seemed possible that China would not be ruled forever by a single party. But that dream ended with Tian'anmen killings. They made little difference, however, to a young graduate who went to work in Shenzhen, formerly a small town that was morphing into a new Hong Kong as it was turned into the world's hub for electronic manufacturing. By the century's end the son was rich beyond his mother's comprehension, and living in a spacious apartment and later buying another one in Hong Kong.

By 2010, after he moved to Shanghai, his algorithms were helping to drive China's Internet shopping rise. By the time he turned 50 he was living in Sandalwood Estates, a gated compound of 16,000-square-foot villas ([Sandalwood Estates 2018](#)), and was a global investor, with a vineyard in Canada, a house in California, and considerable holdings in Europe ([Hanemann and Huotari 2017](#)). His son, born in 1990, was living with his mother in Vancouver, preparing to enter a West Coast university. He was calling himself James ([Huang 2017](#)), drove a \$100,000 sports car, and once in a while took his small stooped septuagenarian grandmother (who would fly in for an annual visit) to relatives whose entire families had moved to Canada or the United States.

This narrative, much as the preceding French story, is entirely fictional yet correct in all of its details: chances are that a search could uncover an actual person whose experience has resembled most of the described realities. The key difference is that what took France a century to accomplish was done in China in less than two generations, and even more remarkable is the fact that the trajectory began from incomparably more desperate, truly existential depths of the greatest famine in history. At the same time, this narrative is not such a surprise but rather an excellent example of a late starter's advantages—mightily aided by nearly four

trillion dollars of direct foreign investment and by transfer (legal and illegal) of the latest technical designs.

This book's *raison d'être* is to offer a systematic inquiry into how such epochal transitions took place, to describe in detail the premodern norms (modal or typical growth rates, common uses and capabilities, aggregates and specific achievements), to follow numerous transition trajectories (ranging from those unfolding across centuries to those accomplished within a single generation), and to outline eventual outcomes now prevailing in societies that have undergone those multifaceted epochal transitions. But before this book gets into detailed topical coverage, it might be useful to offer a brief survey of some key contrasts, juxtaposing pre-transition states and eventual outcomes.

Before and After

Simplifications are always perilous, but I ask those critical readers, who might feel that the following text contains some excessive generalizations and imprecise remarks, for temporary indulgence. Starting in the first topical chapter ([Chapter 2](#)), they will be able to plunge into systematic, nuanced, and abundantly referenced reviews, comparisons, and explanations that should make it clear how much diversity and how many departures and complicating factors are hidden behind the facades of grand universal transitions. I offer these brief before-and-after summaries merely as convenient markers of where we have come from and how far we have advanced.

Demographic transitions

Compared to modern norms, all premodern societies had high fertility rates, commonly with five or six children born per woman. These high birth rates were accompanied by nearly as high death rates. Multiple infant deaths were the norm even during the early modern era. This is how François-Auguste-René, vicomte de Chateaubriand, described his own family's experience in pre-Revolutionary France in his famous memoirs from the grave: "In Saint-Malo, my mother gave birth to a son who died in the cradle

... This boy was followed by another and by two girls, none of whom lived for more than a few months” ([Chateaubriand 1849](#), 21).

High early-age mortalities reduced the average life expectancies at birth to less than 50 years, and supported only very low rates of population growth. Uncertain estimates indicate that during the entire first millennium of the Common Era the world’s population had either declined slightly, had remained stationary, or had grown by no more than about 50%. Recurrent violent conflicts, failed harvests, and epidemics caused substantial population losses that took generations to erase. Most notably, large parts of mid-14th-century Europe lost up to half of their population to bubonic plague (caused by bacterium *Yersinia pestis*), and comparable regional losses were inflicted between 1618 and 1648 by the Thirty Years’ War ([Parker 1984](#)).

During demographic transitions, the gradual decline of birth rates lags behind the progressing decline in death rates, and this lag produces relatively high rates of population growth. At the global level, the result was a temporary period of hyperbolic growth that ended during the late 1960s and has been followed by declining rates of increase. With demographic transitions now accomplished (or significantly advanced) in every major region except for sub-Saharan Africa, low fertilities are accompanied by low mortalities, resulting, once again, in relatively low population growth rates.

Increasing numbers of children and adolescents during the early stages of the demographic transition raise the total dependency ratio: that is, the number of people younger than 14 and older than 65 years of age per 100 people of working age between 15 and 64 years. Then, as fertilities decline, nations enjoy their demographic dividends due to the rising share of economically active adults. If they are accompanied by effective policies, those periods are highly conducive to unprecedented rates of economic growth and to impressive gains in average quality of life: think of Japan of the 1980s, South Korea of the 1990s, China of the first decade of the 21st century. Subsequently, the combination of low fertilities and rising life expectancies (to well above 70 years) results not only in higher dependency ratios and widespread population aging but also in population decline (think of today’s Japan).

But even in Japan the largest cities (including Tokyo, the world’s largest) continue to grow. This growth is just a continuation of another key

transition trend: urbanization in general and growth of large cities in particular. The early-modern world was overwhelmingly rural; now more than half of the world's population lives in cities, and the shares are above 75% in all affluent countries. The urbanization process began to accelerate during the 19th century in Europe and North America, after World War II it had reached high rates in Asia, and its culmination has been the emergence of megacities with more than 10 million people. Cities are the dominant centers of innovation and prosperity (albeit accompanied by an often high degree of inequality)—and are permanent magnets for migration, both intra- and internationally. International immigration has become a highly contentious political and social challenge, but in the long run it is the enormous environmental footprint of large cities that is a more worrisome concern.

Agricultural and dietary transitions

Traditionally, all but a small share of food production originated in low-yield subsistence farming that was unable to ensure a reliable supply of adequate nutrition even for relatively limited and slowly growing populations. Common outcomes of these shortfalls included widespread malnutrition, stunted growth, and recurrent famines ([Ó Gráda 2010](#)). The last famine caused by failed harvests in Japan took place between 1833 and 1837, and in Europe, in Ireland between 1845 and 1849, while famines in parts of Asia and Africa, many caused by violent conflict and deliberate government neglect (the USSR, Maoist China, North Korea, Ethiopia, South Sudan), persisted throughout the 20th century. The most devastating one, in China between 1959 and 1961, was not a result of drought or floods but of deranged Maoist policies ([Dikötter 2010](#); [Yang 2012](#)).

In nearly all premodern societies, overwhelmingly vegetarian diets (commonly more than 80%, and even more than 90%, of all food energy was derived from plants) were dominated by a few staple crops. Consumption of four major grains (wheat, rice, millet, and corn), and also of tubers in the tropics and in the Andean highlands, was supplemented by a variety of pulses (lentils—one of the oldest cultivated species—peas, beans, and soybeans). Typical yields of these traditional cultivars had remained consistently low, with staple cereals often producing only twice the amount of the seeded grain and in some regions annual harvests remained below 1

t/ha (see Appendix) even during the second half of the 19th century ([Smil 2017a](#)).

Harvests had also fluctuated considerably with changing weather or with infestations due to viruses, parasitic fungi, or insects. Even with no or minimal diversion of harvested crops to animal feeding (draft animals subsisted on grazed grasses and on crop residues), traditional harvests produced an average food supply that was adequate during good times in the best-off regions (rainfed Atlantic Europe, Asia's irrigated lowlands with rich alluvial soils) but barely sufficient to ensure nutrition compatible with hard physical work in most premodern settings with poorer soils and in seasonally arid climates.

Agricultural transitions brought a combination of more intensive inputs and new crops, new agronomic practices, and more productive animal husbandry. Improved cultivars of staple crops benefited from rising rates of agricultural mechanization, from regular application of synthetic fertilizers, from widespread (seasonal or supplementary) irrigation, and from use of pesticides, insecticides, and fungicides that reduced often intolerably high pre-harvest crop losses. This modernization resulted in unprecedented yields (up to an order of magnitude—that is, a tenfold difference—higher than in traditional cultivars), in reliably produced surpluses of dominant food crops and in both specialization and diversification of cropping. This high yield eliminated famines, assured abundant high-quality food supplies, and made it possible to divert rising shares of harvests into animal feeding, resulting in higher levels of per capita meat, eggs, and dairy-animal food supply (and, regrettably, also in higher rates of food waste).

Energy transitions

All premodern societies were also constrained by energy supply. Pre-transition societies were energized in ways that remained unchanged for millennia. Human and animal muscles were the dominant sources of kinetic energy: these indispensable prime movers were deployed in agriculture, food processing, construction (often using massed labor), felling of trees, quarrying of stones, mining of ores, artisanal manufactures, and trade and commerce. In some regions animate power needed for many stationary tasks became eventually supplemented by small waterwheels and windmills. Their unit capacities remained limited but, in some regions

(notably throughout coastal Northwestern Europe), their large numbers helped to mechanize milling, water pumping, and metallurgical enterprises.

On the ocean, oared ships were still very common during the late 16th century—in 1571 the famous battle of Lepanto between Christian and Ottoman navies saw more than 200 galleys on each side, and in 1599 the ill-fated Spanish Armada sent to invade England included both galleys and galleasses ([Rodgers 1939](#)). And some large oared ships remained in use until the 18th century even as more efficient (but still relatively slow) sail ships were visiting every continent. Both Swedish and Russian navies still had numerous oared vessels, and Swedish commanders deployed gunned galleys to defeat the Russian fleet in the Second Battle of Svensksund in the Gulf of Finland in July 1790 ([Parker 1996](#)).

Thermal energy (heat) came solely from the combustion of biomass. Woody matter (twigs, branches, bark), crop residues (grain straws, plant stalks, roots), and dried animal dung for household uses (cooking and heating) were collected by women and children. Tree felling on larger scales produced wood for metallurgical charcoal needed above all to fire bricks, tiles, and glass. Outside the well-forested regions, the annual per capita supply of these fuels remained low and this energy deprivation was further worsened because of low efficiencies of traditional fuel combustion. Charcoaling converted less than a fifth of wood into smokeless fuel even during the 18th century, fireplace combustion efficiencies remained below 10%, open fires were even less efficient, and only a tiny share of chemical energy in wax and oil (candles and lamps) was converted to light.

Early stages of energy transitions reduced phytomass fuels to minor shares of primary energy as fossil fuels, starting with coal and progressing to crude oil and natural gas, came to supply nearly all of the world's primary energy. They have also become supplemented by primary electricity generated by falling water (starting in the 1880s), later also by nuclear fission (starting in the 1950s), and most recently by modern wind turbines and by photovoltaic cells and central solar power plants. As a result, modern high-energy societies have been able to displace animate labor by machines, to revolutionize food production, and to expand industrial output even as they have diverted increasing shares of their ample energy supply (converted with improving efficiencies) into nonessential discretionary uses, resulting in unprecedented quality of life, in high levels

of personal mobility and communication ability, and in rapidly enlarged access to information.

Economic transitions

Traditional economies, circumscribed by uncertain harvests and inadequate energy supply, experienced minimal rates of growth, with recurrent periods of decline (brought by often protracted violent conflicts and by devastating bacterial or viral epidemics or pandemics) alternating with spells of stagnation or marginal gains. Best reconstructions put average annual growth rate of the global economic product at just 0.01% during the first millennium of the Common Era. At that rate the total product would take seven millennia to double, and even an order-of-magnitude improvement during the next 500 years brought the rate to only about 0.1% with doubling still taking seven centuries.

Consequently, per capita incomes and averages of accumulated household wealth remained low, and often remarkably unchanged, for centuries as economies were dominated by subsistence food production with more than 80% or even 90% of the population living in villages and engaged in farming, producing only small surpluses to support (few exceptions aside) cities of limited size. Economic transitions transformed the contribution of major sectors. These shifts were driven by demographic, agricultural, and energy transitions, with the key advances in cropping, fuel, and electricity use based on innovations arising from new scientific inquiries based on systematic experiments and on investigation of prevailing practices, material properties, and operational modalities.

Industrial production was often led by highly labor-intensive textile manufacturing, but it could not succeed without expanded mining and innovations in iron metallurgy that led eventually to mass-scale production of inexpensive steel. Construction efforts that led the early economic expansion were needed not only to accommodate large-scale population influx to cities but also to emplace new transportation infrastructures. China was a notable exception, as its construction of canals preceded the introduction of railways by many centuries; in contrast, European and American canal construction peaked just a few decades before the adoption of railroads.

Subsequent advances in transportation saw a series of transitions that kept on increasing the sector's importance and that enabled the rise of truly global trade. Just a few generations after steam engines had transformed land- and waterborne passenger and freight traffic, internal combustion engines, and steam turbines able to convert fuels with higher efficiencies and to deliver higher speeds created new industries that produced ships of unprecedented speeds and capacities and that made it possible to develop automobiles and airplanes. Within a few decades after their introduction, automotive industries became the single largest manufacturing sector in all leading industrialized countries. The final transportation transitions came after World War II, with the adoption of gas turbines in flight, with the electrification of railways, and with the introduction of high-speed trains.

Post-WWII decades have also seen the rapidly rising economic importance of a broad range of services, a category that includes wholesale and retail goods, household improvements, education, financial management, and leisure activities ranging from entertainment to tourism. In all countries that have accomplished their economic transitions, the service sector is now by far the most important contributor to national gross domestic product (GDP). This imperfect but now standard measure of economic accomplishments has charted unprecedented growth rates since the early 1950s, with annual maxima approaching or even surpassing 10% in some countries. When combined with declining fertilities, this growth has produced rapid gains in average per capita income. Moreover, with both food and energy becoming more affordable, the shares of disposable income required to buy good-quality nutrition and adequate energy supply have been falling, and those going to a wide range of consumer goods, education, and travel have been rising.

Another key component of economic transitions has been the rising importance of international trade, both in raw materials (in mass terms led by fuels, ores, and food) and in finished products. Some commodities (most notably obsidian and flint) were traded over relatively long distances even during prehistory, and during antiquity long-distance trade in luxury items connected the empires on the opposite ends of the Eurasian mass as Chinese silk was brought via the Parthian Empire to imperial Rome.

But luxury goods reached only the most affluent segments of traditional economies, which remained dominated by subsistence farming and relied heavily on local inputs. Artisanal production of limited quantities of

consumer items was the norm and the societies were overwhelmingly wooden, with metal devices, tools, and utensils in short supply. Globalization increased the share of international trade to nearly half of the world's economic product, and even low-income families now own many products made of a wide range of materials on different continents and transported in high-capacity container ships.

Environmental transitions

Population, energy, and economic transitions have necessitated greater exploitation of the Earth's resources, including minerals (fossil fuels, ores, construction materials that include sand and stone), phytomass (food, feed and industrial crops, wood for timber and pulp), and ocean zoomass (marine species ranging from tiny crustaceans to massive whales). These exploitations also entailed large-scale degradation of natural ecosystems and reduction of indispensable environmental services, be it due to deforestation (in both temperate and tropical regions); soil erosion; air, water, and soil pollution; or the loss of biodiversity. Many pre-transition environments were deforested or their mineral resources were substantially exhausted, with impacts limited to local or regional scales, most notably around the Mediterranean and in North China ([Smil 2013a](#)). In contrast, the combination of agricultural, energy, and economic transitions has resulted in widespread environmental deterioration and in the emergence of two sets of global problems.

The first one refers to the ubiquity of anthropogenic degradation: in that sense we now have global problems with degradative phenomena ranging from soil erosion, desertification, deforestation, and loss of biodiversity to excessive water withdrawals from aquifers, particulate and gaseous air pollution, and land contamination with heavy metals. The second one refers to the existence of truly global impacts when anthropogenic compounds introduced into the environment become eventually distributed worldwide. This distribution creates an unprecedented challenge because the effective management of the impacts requires concerted global actions and the likelihood of such steps is further diminished by existing, even increasing, economic disparities. Global climate change attributable to anthropogenic emissions of greenhouse gases is by far the most important outcome of environmental transitions because its unchecked continuation poses a major

threat to global economic prosperity and even to the very habitability of some parts of the Earth (IPCC 2014).

This shift might be felt first in parts of the Middle East. Part of our evolutionary heritage is to cope with high heat through perspiration and ensuing evaporative cooling, but even for healthy people this protective mechanism works only as long as the wet-bulb temperature (a measure combining temperature and humidity) stays below 35°C, and the limit is lower for children, for the elderly, and for sick adults.

In concert, interconnected both by direct positive and negative feedbacks as well as by many less obvious synergies, these five grand transitions have created the modern world with all of its admirable advances and improvements as well as with its worrisome socioeconomic divides and environmental concerns. They have also transformed the scale of both common transactions and leading concerns as international and global developments and consequences have become no less important than persistent local and regional preoccupations. The result has been a concatenation of unprecedented gains and losses, advances and setbacks.

On the personal level the most notable entries in the positive category are the elimination of famines, reduced mortalities (particularly in infancy) and lengthened life expectancies, higher per capita incomes, greater accumulations of household wealth, wider opportunities for higher education and for travel, and affordable access to virtually unlimited information. The most challenging negative social outcomes include burdens imposed by aging populations, diffusion of antibiotic-resistant bacteria, increasing intra- and international income disparities, excessive concentration of wealth, poor quality of mass education, a surfeit of dubious information and deliberate misinformation enabled by the Internet, and, above all, extensive degradation of the biosphere and of its irreplaceable services.

Studying the Transitions

Grand transitions have been highly interdependent: tracing the genesis of a specific transition, explaining its progress, and assessing its impact is impossible without referring to other transitions whose trajectories and intensities have been, in turn, influenced by a multitude of other

contributions and interferences. Examples of these realities abound. The first topical chapter of this book deals with demographic transitions. How did this fundamental shift in family and social dynamics, whose consequences have affected every aspect of modern civilization, begin? Was it triggered by a specific development or did it require other concurrent transitions, above all the improvements in survival, health, income, food intakes, and energy use?

One variable stands out: the decline in infant and childhood mortality created “the disequilibrium that triggered not only the fertility transition, but more than anything else reduced the shackles of fatalism which lay behind secularization, the rise of the modern economy, and even the knowledge explosion” (Kirk 1996, 386). But how did it work? Dyson (2001) assumed that this decline took place independently of social and economic development but that it was the key reason for concurrent and subsequent economic advances and changes in social structure. David Canning countered that “the case for the complete independence of demographic processes is absurd” and urged an examination of “important mechanisms that flow the other way, from development to demography that might have substantial effects and would undermine this view” (Canning 2011, 3).

As the European demographic transition was so obviously connected with industrialization, it seems natural to suggest that the onset of the fertility decline was due to rising incomes. The standard reasoning has been that income rise led to the higher-opportunity cost of raising children and that this reality was soon reflected in reduced fertility. In economic parlance, income elasticity with respect to children’s quality (investment in their education) was greater than that with respect to their quantity (high fertility) and this preference resulted in increased investment per child. But Galor (2011b) tested this commonly advanced but “fragile” hypothesis and found it inconsistent with the evidence.

There is no consistent negative correlation between socioeconomic status and the pre-transition fertility, but it is correct to conclude that the forerunners of the transition were among the higher-income groups, while peasants were the slowest to reduce their fertility (Dribe et al. 2014). And when the fertilities began their decline they did so almost simultaneously, during the 1870s, when per capita income differences were as large as threefold and where fertilities were positively correlated with incomes. As

Jane O'Sullivan observed, "interventions to promote prosperity are less cost-effective in priming this cycle than interventions for fertility reduction. The data do not support the claim that 'development is the best contraception.' On the contrary, they present a strong case that 'contraception is the best development stimulus' " (O'Sullivan 2013, 1).

Limits of generalization

Avoiding any simplifying conclusions is perhaps the best advice when studying grand transitions. Inevitably, their trajectories must share many commonalities—but national peculiarities are unmistakable. Even in the relatively most advanced and most prosperous early modern societies (during the 17th century in Europe it was England and Wales and Holland of the Golden Age; in Asia it was Tokugawa Japan and early Qing China), the linked quartet of existential fundamentals of population-food-energy-economy did not begin to change, even approximately, at the same time: commonly, one or two transitions commenced well ahead of the others. Consequently, the nation-specific beginnings of transitions affecting the foundations of modern societies differ not only by several generations but also by as much as hundreds of years.

Perhaps the most notable example of an early start is the English energy transition. In England and Wales coal combustion surpassed wood burning no later than by 1620. By that time, all major coal-mining regions that energized the United Kingdom's economic primacy during the 19th century were already open. By 1700 the United Kingdom derived about 75% of its energy from coal—while in France and Germany coal became the dominant fuel only during the second half of the 19th century, and China began to derive more than half of its primary energy from fossil fuels (mostly from coal) only after 1970 (Smil 2017a). Similarly, the beginnings of demographic transitions go back to the 18th century in the Nordic countries (Johansen 2002; de la Croix et al. 2009), while in the Mediterranean nations, most of that shift has taken place only since the 1950s.

Considerable diversity of traditional social and ruling arrangements, economic organization, resource endowments, and behavioral preferences explains why the transitions that eventually led to epochal outcomes began at different times in different countries (and continents), and why some of them had proceeded relatively slowly (particularly the demographic

transition that took many generations to unfold in some countries), while others (particularly some shifts dependent on technical innovation and also some dietary transitions) were accomplished within a single lifetime, some, to a large extent, even within a single generation (20–25 years).

In some cases, all of these factors had only secondary roles, as the onset of a far-reaching transition could be traced to such idiosyncratic (and completely unanticipated and unpredictable) discontinuities as the fall of a long-lasting empire or defeat in a major war. Japan is an excellent example of these precisely identifiable breaks. Meiji restoration (1868), coming after more than 250 years of the Tokugawa shogunate (1600–1868), began Japan's economic transitions, which had eventually profound global consequences, leading first to the defeat of China in the war of 1895 and Russia in 1905, then to occupation of Manchuria (1931) and much of China (starting in 1937), and to the attack on the United States (1941). The country's defeat in World War II and the American occupation of Japan led to an unusually rapid dietary transition ([Smil and Kobayashi 2011](#)) and it laid the foundation for its admirable but short-lived economic rise.

A major consequence of these variable onsets has been the speed of many recent transitions: in many early starters, transitions advanced very slowly and in a staggered manner, while some late starters' transitions had proceeded concurrently and they ran most of their course in remarkably short periods of time. Economic development of post-Mao China—enabled by concurrent population, agricultural, and energy transitions (and accelerated by mass transfer of advanced foreign know-how that was also supplemented by large-scale theft of intellectual property)—is an unrivaled example of such a delayed catch-up proceeding in unison and at remarkably accelerated pace.

An unpredictable course of many transitions is yet another strong argument against generalizations. By 1900, as steam turbines and internal combustion engines were displacing steam engines, it had to be clear to every informed engineer that it was only a matter of time before the last steam engine would be made. In contrast, nobody could predict either the actual speed or eventual extent of successive waves generated by access to information. When Gutenberg used his invention of movable type to print the first pages of his Bible in 1454, he could not foresee that during the remaining 45 years of the 15th-century European printers would publish more than 11,000 new editions, that the number of new titles would rise by

an order of magnitude during the second half of the 16th century (to about 135,000), and that they would reach nearly 650,000 during the second half of the 18th century ([Buringh and van Zanden 2009](#)).

Book printing, not textiles or tools, was the first mass-scale industry of the early modern era whose impact (is the Enlightenment conceivable without it?) was not obvious at the time of its origins. Similarly, when Tim Berners-Lee released his first World Wide Web browser in March 1991 it was not at all obvious that a near-monopoly in searching would arise. Mosaic, the first popular Internet browser, became available in 1993 and during the next five years, before Google's launch, there was a mini-universe of search engines, from AltaVista and Ask Jeeves to WebCrawler and Yahoo! Search. But then Google either eliminated the competition or relegated other options to marginal shares, and now anybody with a computer or a mobile phone is able to access most of the reproduced, copied, scanned, or encoded historical, technical, medical, and scientific information—as well as to download any recipe, famous painting, photograph, how-to advice, or out-of-copyright book (leaving aside countless pirated editions of copyrighted texts).

But there is one area where generalizations can be widely applied to all types of grand transitions. No trees grow to heaven, and while the expansion limits have been much enlarged during the era of globalization, they eventually assert themselves, growth rates (or efficiency gains or monetary savings) slow down, plateaus are reached, new equilibria are established, companies mature, expectations decline—and speculations begin about the next disruptive shift. Inevitably, there are many irregularities, disruptions, and surprises, but systematic studies of growth (be it of premodern inventions or the latest electronic applications) show remarkable recurrences of expected patterns.

S-shaped trajectories and technical innovations

No matter how gradually or how rapidly the transitions unfold, growth of their critical parameters tends to follow an S-shaped trajectory conforming to a logistic function (characterized by a symmetrical curve) or to one of several similar confined growth patterns ([Smil 2019a](#)). This pattern means that the shift to a new mode, practice, or arrangement begins slowly and that the traditional ways and patterns may continue to gain in importance

for decades after the introduction of new techniques or uses. Well-documented displacement of American draft horses (engaged in field work on farms, harnessed to pull carts and wagons in cities) and mules (overwhelmingly employed in Southern farming) is an excellent example of such a transition (USBC 1975; [Smil 2017a](#)).

At the end of the 1880s, the decade that saw the introduction of the first automobiles and adoption of the first streetcars, the total of these large draft animals had reached 17.5 million ([Figure 1.4](#)). The first tractors for field work were introduced during the 1890s but the total horse and mule count rose to 20 million by 1900. Large-scale expansion of electric streetcars, the construction of the first subways, the introduction of mass-produced passenger vehicles (starting with Henry Ford's Model T in 1908), and growing tractor sales took place before World War I—but the horse and mule count peaked only in 1917 at just over 26.6 million, a third above the 1900 level. By 1930 urban horses were almost completely displaced by electricity and internal combustion engines, but the total tractor count was still less than one million and the United States still had 18.9 million horses and mules, more than in the early 1890s.

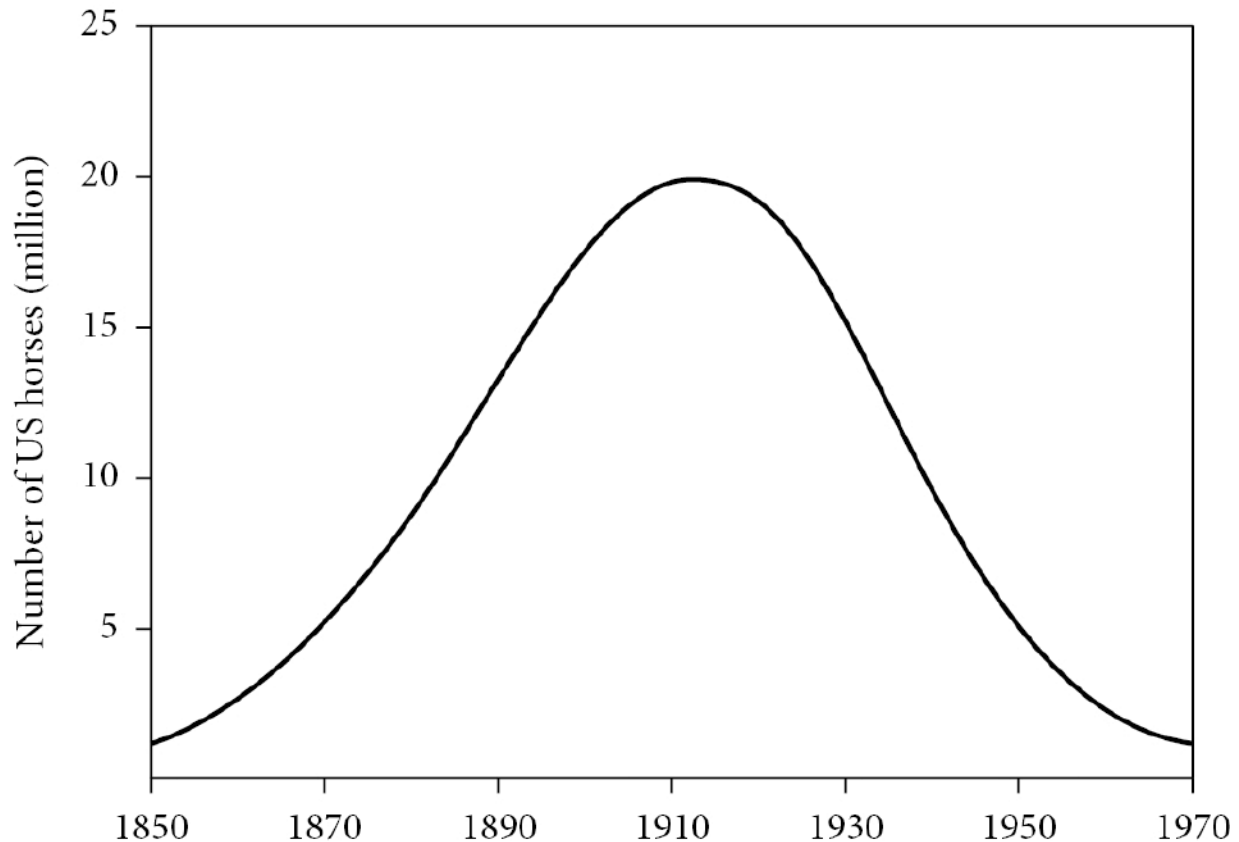


Figure 1.4 Total number of draft horses (and mules) in the United States. The trajectory forms an almost perfect normal (bell-shaped) curve. Plotted from data in USBC (1975).

Mechanization of farming had proceeded during the 1930s despite the economic crisis, and it accelerated after the end of World War II. The 1950 census showed only 7.6 million draft animals, and a decade later the USDA stopped counting them. The epochal transition from horses, animate prime movers that provided draft power for millennia, was thus completed in the United States in about 80 years, and most of it was accomplished in less than half of that time, between 1917 and 1957. This rapid shift looks even more impressive because it had to be accompanied (or preceded) by the development of necessary infrastructures to extract, transport, and process liquid fuels.

Perhaps the fastest epochal transition driven by technical innovation was the switch from waterborne intercontinental travel to flying, and crossing of the Atlantic provides the best example of this process: the speed gain (and hence travel-time reduction) reached an order of magnitude. Leaving aside the early medieval Viking crossings (in open boats), European sailing ships

were the only means to cross the Atlantic between 1492 and 1838. Prevailing westerlies made the eastbound passage faster, but it still took three to four weeks. By the beginning of the 19th century, sailing against the wind by scheduled packet ships took 40 days, considerably longer in stormy weather.

In 1833 the Quebec-built *Royal William* made the first crossing to England and then it took seven more years to pioneer the westward route as two ships arrived almost concurrently. Even with its four-day head start, the *Sirius*—averaging 14.87 km/h and arriving in New York on April 22, 1838, after 18 days, 14 hours, and 22 minutes—barely beat the larger and faster *Great Western*, which averaged 16.04 km/h and arrived the next day, after 15 days and 12 hours of crossing (Smil 2018). The first steam-powered crossing cut the time by more than 60%, and then more powerful steam engines, better hulls, and, eventually, steam turbines kept new records coming. By 1908 the Blue Riband was won by the steam turbine-powered *Lusitania* with four days and 20 hours, and the final record holder, the *United States*, made it in three days, 12 hours, and 12 minutes in 1952 (Stopford 2009). The fastest steam-turbine-powered liners reduced the time needed for the westward crossing by nearly 80%, compared to the first steam-engine-powered run in 1838. An (almost) order of magnitude reduction with steam-powered vessels took more than a century to accomplish.

The era of commercial trans-Atlantic crossings (at least 14 hours), by piston-engine aircraft (starting with Pan Am's hydroplanes), began in May 1939, it was relaunched after World War II, and it was brought to a sudden end by jetliners. Regular trans-Atlantic jet flights began in 1958 when the first turbojet, Boeing 707, cut the trip from New York to London to less than eight hours—and almost immediately the total number of flying passengers surpassed those using (almost daily) liner sailings (Smil 2018). The subsequent transition was very swift: by 1960 jetliners claimed more than 70% of all traffic and although three large new ocean liners were launched during the 1960s (the *France* in 1962, the *Michelangelo*, and the *Raffaello* in 1965), by 1969 ships carried only 4% of all trans-Atlantic passenger traffic, forcing the retirement of the *QE2* in May and the *United States* in November 1969.

Jetliners had eliminated shipping as a commercial option within a decade, one of the fastest epochal transitions on record. The first wide-body jet,

Boeing 747, had entered the service in 1969, making it impossible to resurrect any regular large-scale ocean-borne traffic. Starting with the *Mayflower*, average crossing speeds increased by about two-thirds during the two centuries between 1620 and 1820. First steamers more than doubled it, and by 1952 the SS *United States* (with 66 km/h) was nearly 20 times faster than the *Mayflower*. Compared to the sailing time of some 960 hours during the 1820s, flight time of less than eight hours is two orders of magnitudes shorter, an overall reduction of 99.2%. If it ever comes, affordable supersonic travel could reduce the transit (as did the wasteful, expensive, and abandoned Concorde) to just over three hours. Once the first high-pressure steam engines had been installed on vessels, it was clear that it would be only a matter of time before an epochal transition from wind to steam would be accomplished, and the same was obvious with the advent of jet-powered aviation.

Expectations and realities

But not every shift and not every important adjustment will turn out to be a beginning of a far-reaching transition. A promising takeoff may soon amount to just a false start, and sometimes even a successful takeoff followed by relatively mass-scale development is not enough to result in really epochal change. The history of electric cars offers an excellent example of a false start, and the history of nuclear electricity generation illustrates a trajectory that, contrary to enormous expectations and very large investments, has not lived to its promise: predicted transition to a near-universal dominance of fission power failed to take place.

The first prototypes of modern road vehicles, driven by Gottlieb Daimler and Karl Benz in 1886, were powered by gasoline-fueled internal combustion engines—and so were most of the new (expensive) car models introduced during the following decade. But Edison firmly believed that electric cars would prevail, and his company offered Henry Ford, at that time employed as the chief engineer at Detroit Edison Illuminating Company, the general superintendence but, according to Ford's own description, "only on the condition that I would give up my gas engine and devote myself to something really useful" ([Ford 1922](#), 24). At the beginning of the new century it was not clear which mode of locomotion would eventually prevail. Odds were against steam-powered cars (too heavy, too

tricky to operate)—but electric vehicles looked promising. In the first American track race, in 1896 at Narragansett Park in Rhode Island, a Riker electric car decisively defeated a Duryea vehicle; in 1899 a bullet-shaped French electric car named *La Jamais contente* (Never satisfied) was the first road vehicle to reach the speed of 100 km/h.

Commercial production of American electric vehicles started in 1897 when the Electric Carriage and Wagon Company introduced taxicabs in New York. By 1899 the nationwide annual output of electrics surpassed 1,500 units, compared to 936 gasoline-powered vehicles, and by 1901 Pope's Electric Vehicle Company became both the largest producer and the largest operator of motor vehicles in the country ([Burwell 1990](#); [Kirsch 2000](#)). Electrics were advertised as “absolutely safe, perfectly clean, best to ride and most economical to keep.” They were also quiet and required no refills with flammable gasoline and no laborious, even dangerous, cranking, as did all internal combustion engine vehicles before the mass adoption of electric starters ([Smil 2005](#)). And the first steps were taken to put in place the requisite infrastructure: six charging stations were built between New York and Philadelphia, and Edison, firmly convinced that the future belonged to the electrics, embarked on the development of a better battery ([McShane 1997](#)).

But Edison was wrong. He spent the first decade of the 20th century in developing a better battery—and he did, but it was not a better car battery. His nickel-iron battery had a long lifetime and higher energy density than the lead-acid battery invented in 1859, and it was also very sturdy. Moreover, it had low voltage and a low charging rate but higher mass and volume. Edison's battery—in commercial production until 1975 (used mainly in underground mining and by railroads)—did nothing to prevent the triumph of internal combustion engines. New York's Electric Vehicle Company had first reduced its operation to occasional rides in Central Park and went bankrupt in 1907, even before Ford introduced his Model T in October 1908.

No major move toward electric road transport took place until the very end of the 20th century. In 1995 the California Energy Commission set the target of 2% of all new vehicles sold in the state to be electric in 1999, but no commercial electrics were actually sold ([Lazaroff 2001](#)). The outlook had finally shifted as a part of a broader quest for the decarbonization of energy supply. We are, finally, in the early stages of another epochal

transition, from internal combustion engines to electric motors in road transport: more than a century after they were first widely seen as the best choice, electrics are finally ascendant. But it will take many decades to complete this transition ([Smil 2017c](#)).

The International Energy Agency sees as many as 70 million units worldwide by 2025 and 160–200 million by 2030, and the span of all forecasts published for that year is between 30 and 200 million electric vehicles.

My best forecast is for 360 million electric vehicles by 2040, compared to BP's forecast of 320 million ([IEA 2017b](#); [Smil 2017b](#); BP 2018a). Bloomberg New Energy Finance expects that by 2040 electric vehicles will be just over 30% of the total passenger fleet, but with about 1.7 billion vehicles on the road this statistic means that internal combustion engines would still dominate (BNEF 2020).

Electricity produced by nuclear fission was widely seen as an epoch-making departure even before the first commercial nuclear power plant went online. That hope was most famously expressed in 1954 by Lewis L. Strauss, at that time the Chairman of the US Atomic Energy Commission, who assured the National Association of Science Writers in New York that nuclear electricity will be “too cheap to meter” ([Strauss 1954](#)). Commercial generation began in 1956, and while the subsequent rise (in the United Kingdom, United States, and the USSR) was slow—nuclear generation supplied just 1% of the world's electricity by 1968—that is not unusual in early stages of technical advances.

In the early 1970s it was widely expected that by the year 2000 not only would all US electricity generation be nuclear but also most of it would come from the much more efficient fast breeder reactors that were at that time under intensive development in several countries ([Smil 2017b](#)). The global share of nuclear generation rose to 5% of all electricity in 1975, doubled to 10% by 1981, and reached 15% just three years later, but this rapid pace merely reflected the delayed completion of a wave of power-plant orders during the early 1970s, not the new industry's future. New US orders ceased by the end of the 1970s (not because of the safety fears engendered by the Three Mile Island accidents, but mainly because of cost overruns); similar orders had (France excepting) almost stopped in Europe and they slowed down in Japan and in the USSR, particularly after the Chernobyl disaster in 1985. The share of nuclear generation peaked at

16.8% of the world's electricity in 1987 and then stagnated around that level for the remainder of the 20th century.

What seemed in the 1950s a highly promising beginning of a new epochal transition has turned out to be just a costly start of a deeply flawed electricity generation technique. And there is no realistic chance of a second coming. In 2020 the world's nearly 450 reactors in 28 countries produced about 10% of all electricity. The International Atomic Energy Agency sees the share of nuclear electricity in total global electricity production declining to 7.8% in 2030 and to 6% in 2050, while a high scenario has the share increasing to 12.4% in 2030 and to 13.7% in 2050, still well below the record rates of the 1980s (IAEA 2018). This estimate means that nuclear electricity would be less than 4% of the 2050 primary energy supply.

Unprecedented outcomes

What unites all of these disparate but interrelated transition processes is that their final outcomes (regardless how much they may have differed from initial expectations) were truly unprecedented. Societies that have undergone all four grand transitions have emerged into an era of entirely different population dynamics, food surpluses (and food waste), high levels of energy use (and, again, of excessive waste), and expanding economic opportunities (accompanied by growing wealth inequalities). Readers of this book who live in affluent countries have benefited from these synergistic transitions in more ways than they would guess without trying to make a basic list of gains and advantages. Moreover, most of them take the accomplished outcomes for granted, regarding them as fully expected and somehow entirely unsurprising results of seemingly preordained progress: could there have been any other endings? Of course, there could have been, and hence it is not a foregone conclusion that these benefits will be fully extended to those populations that have been, so far, less fortunate.

Lives of billions of people in low- and middle-income countries now take place at different stages along the specific trajectories of the four grand transitions. A visitor who knows nothing about China may feel that the country is technically ahead of the United States when he steps out of a maglev train that brought him from the airport to Shanghai's Longyang station. But the German-made train is the world's only and a highly subsidized showpiece of its kind, and the traveler would get very different

impressions of China if he could see daily lives of peasants in rural Guangxi or coal miners in Shanxi. And if the new China is not the world's most unequal modern society, then it surely is among the top three contenders for this unenviable ranking. There is a similarly unequal distribution of wealth in India, and the country contains groups of tens of millions of people who could be placed at every stage of the transition continuum, with the extremes of this reality all too visible as Mukesh Ambani's billion-dollar house towers above the slums of Mumbai.

And there are additional hundreds of millions of families (most of them in Africa) who remain largely untouched by these four grand transitions. They still live as subsistence farmers (or herders) with half a dozen (often malnourished and stunted) children and with continuing threat of unpredictable food shortages. These pre-transition families still burn wood or straw (outdoors or indoors, causing respiratory problems) to cook meals, and their women and children still walk long distances to gather firewood and to fetch water from wells or ponds. They still live almost completely outside modern economic exchanges of labor and products, and their accumulated wealth amounts to just a few basic survival items: simple frame beds, some pots and cooking utensils, a change of clothes.

The moral imperative of sharing the benefits of grand transitions has become even more acute during the past generation, as so many signs have been pointing to increasing global economic inequality—but this desirable quest also makes it even harder to contemplate the prospects of reconciling these needed shifts with the long-term preservation of the biosphere that is already under a multitude of serious pressures even as billions are yet to experience a decent quality of life. That dilemma is whether the management of the fifth transition will determine the real success or eventual failure of the first four epochal shifts, and at this point it is impossible to say if we will succeed (at least to a large extent) or if we will largely fail in the most fundamental quest, that of maintaining a habitable biosphere.

2

Populations

Demographic transitions have resulted in an epochal shift that was engendered by other major, unprecedented transformations and that has, in turn, brought a variety of social, economic, political, and environmental consequences. Inevitably, this process has been a major subject of modern population studies ever since its notion emerged during the 1930s. Here is Ronald Lee's concise description of the process: "Before the start of the demographic transition, life was short, births were many, growth was slow and the population was young. During the transition, first mortality and then fertility declined, causing population growth rates to accelerate and then to slow again, moving toward low fertility, long life and an old population" (Lee 2003, 167). Resulting trajectories have been often shown in a stylized simplification (Figure 2.1) but, as expected, actual national sequences show many departures from this idealized pattern.

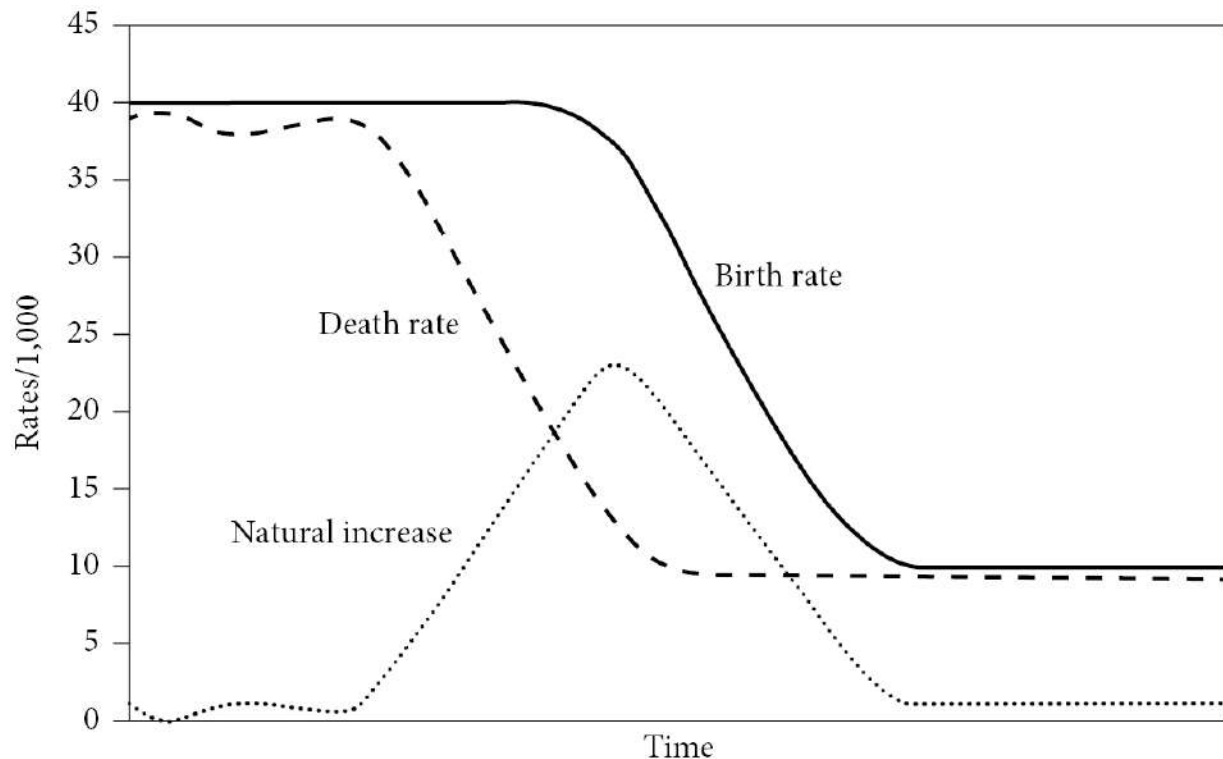


Figure 2.1 Simplified trajectory of the demographic transition, showing successive declines of death and birth rates and the resulting temporary increase in natural growth rate.

In the long run, the fortunes of any species depend on its population dynamics. Consequently, one would expect demographic transitions, so obviously central to the creation of the modern world, to have received a great deal of attention by studies ranging from economic development to environmental degradation. Curiously, this has not been the case. As Tim Dyson concluded, the role of demographic transition “has generally been underestimated” and “unless development theory puts the demographic transition at its core, it cannot adequately account for key social-structural transformations which are integral to the concept of development” (Dyson 2001, 67). Similarly, Ronald Lee and David Reher rank this historical “secular shift in fertility and mortality from high and sharply fluctuating levels to low and relatively stable ones . . . as one of the most important changes affecting human society in the past half millennium, on a par with the spread of democratic government, the industrial revolution, the increase in urbanization, and the progressive increases in educational levels of human populations” (Lee and Reher 2011, 1).

And yet these have not been generally shared appraisals, even among demographers. The meaning of the shift has been disputed and even the very existence of the phenomenon (despite having been a matter-of-fact subject of demographic studies for decades) has been questioned and dismissed. Simon Szreter acknowledged it as a great graphic metaphor that describes, and predicts, an overall long-term pattern of change, but believed that it provides no heuristic guide to understand specific fertility changes in historical circumstances: “the idea of demographic transition is not only unnecessary but also inappropriate” (Szreter 1993, 692). No less dismissively, Nielsen sees the demographic transition theory “repeatedly contradicting empirical evidence . . . by placing full trust in stories based largely on creative imagination” and concludes that its continuing use makes the demographic research unscientific (Nielsen 2015, 17).

These rejections stem from asking for something impossible: national trajectories show significant departures from the theory’s idealized conceptualization and I will point out many of these specific realities—but to deny the epochal (and by now, except for Africa, a universal) shift from high to low fertilities and from high to low mortalities is to ignore the most fundamental demographic evidence. In their eagerness to expose the inability of a generalized model to replicate many nation-specific historical experiences the critics of demographic transition err by questioning the very existence of such an undeniable, and a hugely consequential, phenomenon.

In order to understand the process and to appreciate inevitable departures from an idealized sequence, it is necessary to start with a brief primer introducing key demographic variables. Growth of human populations (natural increase) is driven by the difference between birth and death rates. Both of these events have their natural limits but both can be affected internally (by specific preferences and choices) and externally (by factors ranging from diseases to medical advances). Birth rates (natalities, number of children born annually per 1,000 people) are constrained by fertility rates (the total number of children born to a woman during her childbearing years) and those have natural maxima determined by the number of ovulation cycles, conception rates, and pregnancy losses.

Unconstrained birth rates range between 40 and 50 live births per 1,000 people a year—but in many traditional societies the rates were considerably lower. Some populations reduced them by resorting to relatively large-scale celibacy, particularly within religious orders in Europe (Parish 2010), and

with Buddhist monasteries in Tibet or Thailand ([Pichard and Lagirarde 2014](#)). Many traditional societies practiced pregnancy avoidance (postponement of marriages and proscription of premarital sex) or contraception (*coitus interruptus*), and infanticide (especially of newborn girls) was a common way to regulate the number of surviving children ([Riddle 1992](#); Jütte 2008). As a result, some premodern fertilities were not close to natural fertility maxima.

Death rates (mortalities) are expressed either as totals of all deceased per 1,000 people or, in age-specific terms, for 1,000 people in major age groups (infants, children, adolescents, adults, elderly over 65 or 85 years of age). Death rates in premodern societies were always high, mainly due to infant mortalities commonly higher than 300/1,000 live births (more than 30% of newborns died before their first birthday). Even in late-19th-century Europe, when infant mortalities declined to about 100/1,000 live births in Norway and Sweden, they remained between 200 and 250/1,000 in Germany, Austria, and Russia ([Berin et al. 1989](#); [Viazzo and Corsini 1993](#)). Childhood mortalities were also high and infections and injuries reduced adult survival.

The combination of high natalities and high mortalities resulted in very slow population growth in all traditional societies, and its further temporary reductions (brought by recurrent epidemics, pandemics, prolonged violent conflicts, and consecutive poor harvests) led to often significant population declines. All premodern population estimates have considerable degrees of uncertainty, but the best evidence indicates that global population growth rates were less than 0.05% before the year 1000 and that they more than doubled to about 0.1% during the first half of the second millennium of the Common Era. The rate doubled again during the 16th century, rose to about 0.2% during the 18th century, and quadrupled to 0.8% during the 19th century; before it began to fall it reached briefly, during the 1960s, peaks just above 2%, with the 20th-century mean at 1.35% ([Figure 2.2](#); [Smil 2019a](#); [UN 2017b](#)).



Figure 2.2 Annual growth rate of the world's population, 1700–2020, and the UN's medium projection for 2025. The rate peaked during the late 1960s at just above 2% and it is expected to decline to less than 0.5% by 2050, returning to the norm that prevailed during the late 18th century.

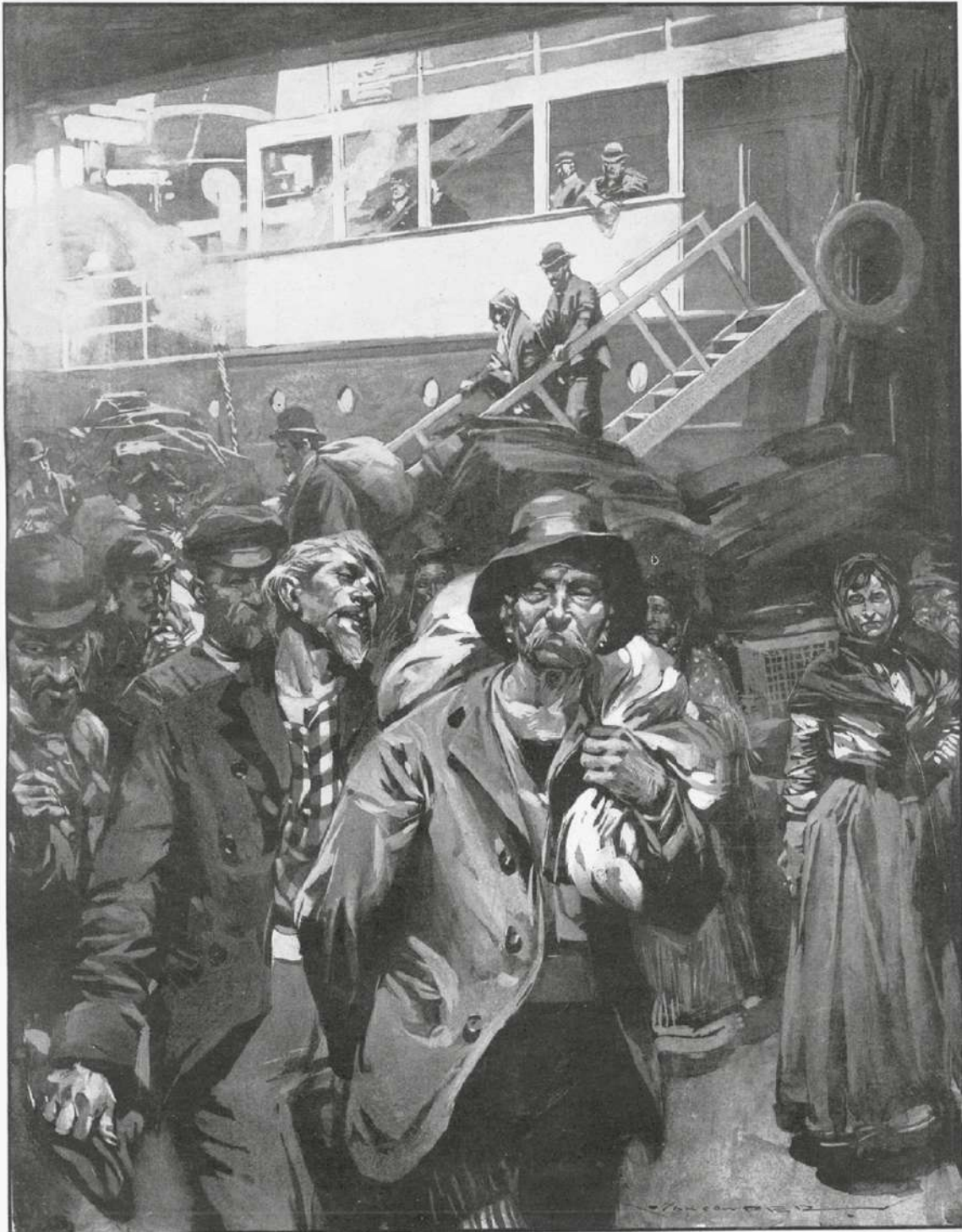
The very low rates of premodern growth mean that on the linear scale the plot of annual global population totals for the entire span of about 5,000 years of recorded history consists of a nearly flat pre-1500 line followed by a slight rise before 1800 and then by an almost vertical ascent. This rapid temporary increase in population growth has been the transition's most important consequence, but in those countries that have completed their demographic transition the main preoccupation is now with population aging.

I will close this chapter with a brief survey of urbanization, the shift that could not have taken place so rapidly and to such an extent without the combined push of mass-scale emigration from the countryside and the pull of city-centered industrialization (and, later, the rise of a large-scale urban service sector). The urbanization process began to accelerate by the middle of the 19th century, and once the shift had become truly global 100 years later, by 2007 half of humanity resided in cities. Urbanization has had particularly strong effects on all processes considered in this inquiry: it has

reduced fertility, increased demand for a greater variety and better quality of food, multiplied average energy uses when compared to rural settings, transformed the global economy, and exerted considerable pressure on the environment.

Pre-WWI urbanization had a significant component of international migration that had a particularly important role in the emergence of the United States as the world's leading economic power ([Figure 2.3a–b](#)). By 1910 the decennial census showed 13.5 million Americans born abroad, 87% of that total in Europe ([Gibson and Lennon 1999](#)). After an interwar slowdown, European outmigration resumed after 1945 and then declined with rising prosperity while the immigration from the Middle East and Africa became a major concern for the European Union during the early 21st century.

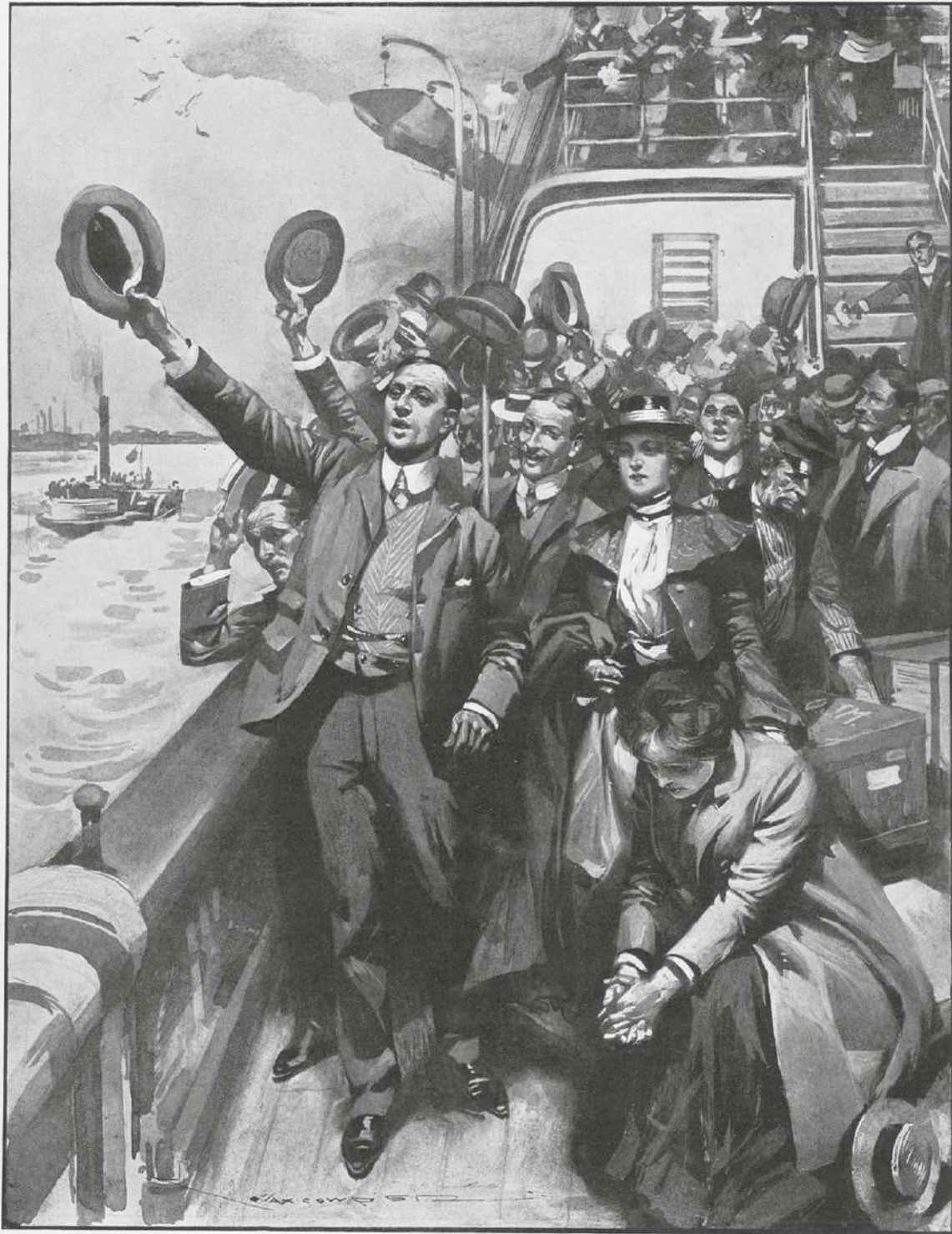
(a)



IMMIGRANTS.

Figure 2.3 a and b Two classes of immigrants arriving in the new world at the beginning of the 20th century. European emigration included both well-educated and enterprising individuals and workers who were willing to labor in fields, mines, and factories. Images from the *Illustrated London News* of August 22, 1903.

(b)



EMIGRANTS.

This immigration has been created by the pull factor of declining fertilities throughout the continent and the push factor of the massive bulge of young people (especially men between 14 and 26 years of age) from

African countries, the Middle East, Afghanistan, and Pakistan. This mass movement could be thus seen as the most recent, the fourth, outcome of population transitions. The influx of more than one million of these migrants to Germany in 2016 was the most obvious demonstration of the potential intensity of this migration, but the cumulative numbers of migrants coming to Italy and Spain from North Africa have remained high for much longer, and there are similar concerns as migrants from Latin America, Asia, and Africa move to North America and Australia.

Transitions in mortality, fertility, and migration share several essential features ([Willekens 2014](#)). They are collective outcomes of individual actions, choices, and preferences, especially in their later stages, when personal autonomy and the ability to choose increase as the role of institutions and social structures declines. Their trajectories are often determined by their history, the reality that is often labeled as path dependence, as many early events and actions carry long-term consequences and determine future feedbacks. They are diffusion processes with different mechanisms and specific adoption rates.

Demographic Transition

The concept of this epochal population shift was first outlined in 1929 by an American demographer, Warren Thompson ([Thompson 1929](#)), and it was succinctly defined a few years later by Michel August Adolphe Landry, a French demographer:

Sous l'effet de profondes transformations économiques et sociales, toute population est appelée à passer, à un certain stade de son histoire, d'un équilibre entre haute fécondité et haute mortalité à un nouvel équilibre entre basse fécondité et basse mortalité (Because of the effect of profound economic and social transformations, every population at a certain stage of its history is expected to move from an equilibrium of high fertility and a high mortality to a new equilibrium that balances low fertility and low mortality) ([Landry 1934](#), 7).

This straightforward description conveys the essence of the transition, but its studies have uncovered many national specificities and notable exceptions, and by far the most interesting challenge has been the quest to unravel the causes and to understand the consequences of this process. Its first extended formulations came in 1945 (Notestein 1945; [Davis 1945](#)) and since the 1950s it has been a key subject of modern demographic as well of

economic and sociological studies ([Chesnais 1992](#); [Szreter 1993](#); [Kirk 1996](#); [Reher 2004](#); [Caldwell 2006](#); [Lee and Reher 2011](#); [Canning 2011](#); [Diebolt and Perrin 2017](#)). During that time, the demographic transition became a global process: it continued in Europe and North America, unfolded rapidly in East Asia, and eventually began even in some African countries. The proximate prime mover of the transition is the reduction of fertility—and only a few basic facts and assumptions are needed to calculate maximum average fertilities and hence to appreciate the extent of their subsequent reduction.

Fertility rates

The natural fertile life span of healthy females (ignoring modern medical interventions that can result in pregnancies in women well over 50 years of age) extends from menarche to menopause. During the premodern era, the average age of menarche was relatively late, in many cases not before the age of 17. By the middle of the 19th century, it was just over 15 years in Western countries, and the secular trend during the 20th century, a decrease of three to four months per decade, brought it down to less than 13 years by the 1980s, but the downward trend seems to have stopped since ([Clavel-Chapelon 2002](#)). The age of menopause has seen a much smaller concurrent shift and it now extends to just over 50 years. Average length of reproductive age has thus increased slightly during the 20th century to about 38 years ([Nichols et al. 2006](#)).

In premodern societies the average fertile span, reduced by premature mortality, was only about 30 years or nearly 400 ovulations. In addition, every pregnancy subtracted 10 ovulations, and breastfeeding, the norm in traditional societies, greatly reduced the chances of conceiving for at least another five to six months. The theoretical fertility maximum for a woman would be on the order of 25 children, and with multiple births there are several reliably verified records of more than 30 live-born offspring. Premodern-populations pregnancy loss among fertile women was significant, and with the maximum efficiency of human reproduction of about 30% per cycle the average maximum total fertility rate (TFR) is about 8–9 children, and it is further reduced by 10% due to typical prevalence of infertility.

Average fertilities of 7 to 8 children per lifetime should be thus taken as representative maxima for entire populations, they were still found during the closing decades of the 20th century in parts of Africa and Asia, and still prevail in several African countries. According to the 1986 census, average TFRs in Iran's rural areas ranged between 7.5 and 8.5 during the early 1980s (Abbasi-Shavazi et al. 2009), and in 2017 Niger had the world's highest mean rate with about 7.5 children, followed by Somalia with 6.2, while 11 other African countries (including Nigeria, the continent's most populous nation) and Timor-Leste had rates between 5 and 6 ([World Bank 2019](#)).

Moreover, these high rates are actually lower than the desired number of children, according to surveys of married women conducted between 2004 and 2008, when the preferred African totals were as high as 9.2 in Chad, 9.1 in Niger, 6.8 in Congo, and 6.7 in Nigeria (USAID 2010). In contrast, the preferred numbers of children in China and India were just 2, slightly lower than in the United States or the United Kingdom. African rates are multiples of replacement fertility, the average number of children born per woman that is required to maintain the existing population from one generation to the next. That rate is about 2.1 in affluent populations (an additional 0.1 is required to compensate for those girls who will die before reaching their fecund age) but it may be considerably higher (even above 3) in countries with high infant and childhood mortality, where a much higher number of girls may not live to reach their reproductive age.

But has this transition from very high to replacement (and lower) fertility been a universal experience? Susan Hanley questioned its validity for Japan as she concluded that there was no sharp discontinuity between the population dynamics during the Tokugawa period (1604–1861) and that of their descendants not just during the Meiji period (1868–1912) but even during the 1920s, because the traditional populations had low birth rates and relatively high life expectancies ([Hanley 1974](#)). But Carl Mosk refuted that conclusion by pointing out that we do not have trustworthy information either for Tokugawa or Meiji population dynamics: evidence comes from a small number of villages, there are large spatial and temporal variations, infants' deaths were underreported, and the low birth rate can be explained by low fecundity due to poor diet creating temporary sterility and causing long intervals between births ([Mosk 1977](#)). Consequently, there is no reason to reject the concept of a demographic transition for Japan.

Similarly, some demographers and historians have maintained that China's pre-transitional marital fertility was lower than in Europe and that both the number and sex of children and spacing of births were deliberately controlled ([Campbell et al. 2002](#); [Zhao 2006](#)). But we have to be very careful when using such rates to reconstruct population dynamics of traditional populations. On the one hand, the best available evidence—be it for China ([Campbell and Lee 2010](#)) or Germany ([Amialchuk and Dimitrova 2012](#))—does confirm that traditional populations practiced parity-specific control of marital fertility (trying to avoid conception after having the desired number of children) as well as non-parity-specific control, either by trying to reduce the chances of conception or by lengthening the time between successive births.

On the other hand, underreporting of births as well as of infant deaths was common, and even the prevalence of indisputably low fertilities cannot be ascribed (solely or largely) to deliberate controls of marital conception. Alternative explanations include low coital frequency, amenorrhea due to long periods of breastfeeding, lowered fecundity, and temporary sterility. The last two conditions were induced by chronic malnutrition or undernutrition or by untreated diseases, and they could explain long inter-birth intervals ([Amialchuk and Dimitrova 2012](#)).

Historical evidence shows that deliberate regulation of childbearing was gradually evolving long before fertilities began their clearly noticeable secular fall. These measures could not produce dramatic reductions in the total number of children but they were effective enough to make a difference and to question the generic model of transitional phases (but not the very notion of the transition itself). Dudley Kirk saw the essence of the process as “the transition from primitive conditions of wasteful mortality and reckless procreation to a new balance of low death rates and controlled fertility” ([Kirk 1946](#), 242).

There is no doubt that some early modern European and Asian populations had moved considerably away from “reckless procreation” already during the 17th and 18th centuries. Consequently, it would be mistaken to assume the prevalence of high “natural fertility” in all pre-transitional populations—but it was only during the first half of the 19th century when the leading European countries began to reduce their traditionally “wasteful mortality” even as they kept on lowering their fertility. John Bongaarts identified seven proximate determinants of fertility

in modern societies—the proportion of married women among all women of reproductive age; contraceptive use and effectiveness; duration of postpartum infecundability (or postpartum insusceptibility); induced abortion; fecundability; prevalence of permanent sterility; and spontaneous intrauterine mortality—with the first four variables explaining most of the variation among diverse populations ([Bongaarts 1978](#)).

In premodern populations, marriage at an early age was the norm, traditional contraceptive methods were largely ineffective, postpartum infecundability did not reduce fertilities to any significant degree, and induced abortions were not common (but selective infanticide of girls was not unusual).

Michel [Landry's \(1934\)](#) classic conceptualization of the process is as follows. Traditionally, the majority of people subsist at only the minimum existential level, births are unlimited, and populations are regulated by mortality. Then comes the control of fertility through nuptiality (celibacy or late marriage) as the parents strive to provide their children with a standard of living that is at least equal to their experience. The final stage is control of fertility in marriage done for economic and other reasons, the option made highly acceptable thanks to low infant and childhood mortalities.

Transition trajectories

American demographer Frank Notestein identified three stages of demographic transition that describe the basic dynamics, and this division became a common model of the process (Notestein 1945). Countries where the transition has not started experience irregular growth that remains low on average (the pre-transition stage). Where the transition has been under way for some time, mortality has been lowered while fertility has not been similarly reduced and this combination produces maximal growth (early transition). During the third (late transition) stage, mortality is greatly reduced, birth rates keep falling, and population growth decelerates. During the post-transition stage, fertility is well below the replacement level and its drop eventually results in population decline.

Idealized illustration of this sequence has been commonly reproduced to represent the typical process of demographic transition (see [Figure 2.1](#))—but reconstructions of actual long-term trajectories for a number of countries with reliable historic data show many departures from the

simplified sequence. That no two countries have followed identical trajectories comes as no surprise, given the many population-specific combinations of nuptiality, fertility, mortality, and migration that can prevail at any stage of the transition. As [Kirk \(1996, 386\)](#) concluded, “this diversity is not irreconcilable with the universality of the transition. . . . But . . . the differences are not so great. They may accelerate or delay the transition, but the transition itself is inescapable.”

Population statistics are not sufficiently detailed for reconstructing pre-1850 fertilities, but several European countries have good birth and death registries going back more than 250 years, and the mortalities and natalities for England and Wales go back to the mid-16th century ([Wrigley and Schofield 1989](#); [Chesnais 1992](#); [Binion 2000](#); [Wintle 2000](#); [Reher 2004](#); [Caldwell 2006](#); [Bocquier and Costa 2015](#); [Diebolt and Perrin 2017](#)). The oldest available series show birth rates fluctuating between high rates (on the order of 40/1,000, corresponding to TFRs > 5) and moderated levels (on the order of 30/1,000, corresponding to TFRs of around 4), with death rates (also considerably fluctuating) nearly matching them. Reliable Danish and Swedish vital statistics go back to the first half of the 18th century ([Andreev 2002](#)).

Population dynamics of England and Wales provide well-documented early examples of distinct and often prolonged stages that closely correspond to an idealized transition model ([Wrigley and Schofield 1989](#)). In countries with reliable statistics, we can pinpoint the onsets of sustained decline in birth rates to a specific year: to an exceptionally early start in 1827 in France, and to 1877 in Sweden, 1881 in Belgium, 1887 in Switzerland, 1888 in Germany, 1893 in the United Kingdom, 1897 in the Netherlands, and 1898 in Denmark. The decline began in nearly all European countries before the beginning of World War I. But there are many national idiosyncrasies with notable differences in the prevailing pre-transition patterns of fertility, its trajectory (lags in mortality and natality declines, rates of the shifts), and its new low-level equilibria.

Western Europe and East Asia had two very different marital patterns during the pre-transition era. In East Asia the age of marriage for women was low (even extremely low) and marriage followed by early pregnancy was almost universal, but marital fertilities were commonly low, sometimes extraordinarily so, and the transition’s most remarkable shift was in higher marriage age rather than in much reduced marital fertility. In contrast,

European women married relatively late and many remained single. European birth rates were thus fairly low (30–40/1,000) while marital fertilities were high. Remarkably, once the marital fertilities had begun to fall, so did the average age of marriage while the share of married women rose.

Europe's demographic transition was very closely linked to the industrial revolution and urbanization, but there is no easily identifiable transition-inducing threshold that could be quantified either in terms of average economic product or in terms of social progress (above all access to education, particularly for girls). In turn, these shifts were enabled by the epidemiological transition as the frequency of infectious diseases was gradually reduced (and for some eventually eliminated) and as chronic degenerative diseases (led by cardiovascular illnesses and cancers) became the leading causes of death. Sustained reduction of fertility became a matter of conscious choices as families, weighing their socioeconomic conditions and their children's prospects, made rational calculations to limit their size (Coale 1973).

But one generalization appears to hold well for European countries as well as for Asia and Latin America: late starters proceed faster than do the early adopters. Compared to Northern Europe, the transition process was much faster in Mediterranean countries as well as in Russia, while France had forged its own unique pattern (Chesnais 1992; Binion 2000; Diebolt and Perrin 2017). In 1800 the country's average TFR was just 4.5, compared to 7 in the United States, and the French fertility decline began at least several decades and up to a century earlier than that of its neighbors. Cummins (2012) argued that this decline resulted from changing levels of economic inequality associated with the 1789 Revolution, but the process had certainly other causes. The British birth rate fell below 30/1,000 only during the 1890s, while in France it had been below that level since the 1830s. Moreover, the French mortality and natality began to decline at about the same time and continued to do so at very similar rates.

In post-1950 East Asia the shift to below-replacement fertilities proceeded with unprecedented speed. Demographic transition took generations to complete in some European countries: two centuries in Denmark (from 1780 to 1980) and nearly two centuries in England and Wales (from the early 1760s to the early 1940s) as well as in Sweden, where the onset dates to about 1810 and the end to about 1980. In contrast,

Taiwan's trajectory combined rapid decline in mortality with a much delayed (by about 50 years) decline in natality, and the transition was accomplished only a century after it began. China, South Korea, and Iran are the best examples of populous countries whose transitions were accomplished within times shorter than the average life spans of their citizens.

China experienced rapid fertility decline even before its enforced one-child policy (in effect between 1980 and 2015): the nationwide mean was about 6 in 1950, it rose to about 6.4 in 1965—the compensation peak that followed deaths of some 40 million people during the 1959–1961 famine—and declined to about 2.6 in 1980 ([World Bank 2019](#)). The one-child policy pushed it to just 1.5 in the year 2000 and by 2015 it rose slightly to about 1.7. Remarkably, the South Korean TFR decline, achieved without any government intervention, was even faster, from 6.1 in 1960 to 1.57 in 1990, and then to just 1.2 by 2015. And the world's lowest fertilities are now also in East Asia: besides South Korea, rates below 1.3 have prevailed since 2000 in Taiwan and Singapore as well as in Hong Kong and Macau.

Brazilian decline was also rather precipitous, from 6.1 in the early 1950s to 2.1 at the beginning of the 20th century and to 1.75 in 2017. Nothing, however, has surpassed the celerity of the shift in Iran. When the mullahs took over in 1979 the country's TFR was about 6.5 and still 6.2 in 1986, when a new census revealed a rapidly growing population. Subsequent antinatalist policies brought the rate to the replacement level by the year 2000 and recently it has declined below 1.75 (Abbasi-Shavazi et al. 2009; [UN 2017a](#)). During the second decade of the 21st century, only some Middle Eastern countries and most of sub-Saharan Africa were still far from closing the gap between their falling mortality and relatively high natality. Nigeria, Africa's most populous country, has cut its death rate by half since 1960 but it has reduced its birth rate by just 15%. During the same period Egypt cut its mortality by 70% but its natality by only 43% ([World Bank 2019](#)).

Several Western European countries accomplished most of their transition during the 19th century, when they halved, or nearly halved, their mortality while their birth rates continued to decline at similar rates. Both of these declines continued until the 1940s as many European populations arrived at a new equilibrium of very low natalities and mortalities (both on the order of 10/1,000): their demographic transition was essentially

completed. But right after World War II, Europe and North America experienced two decades (1945–1964) of relatively high fertility commonly known as the baby boom ([Monhollon 2010](#)). The length of this fertility reversal indicates that it was more than the catch-up with postponed wartime childbearing: the trend toward larger family size began in the late 1930s, and higher marriage rates and lower marriage age were other factors.

The fertility decline that had resumed in Europe and North America during the late 1960s has been called the second demographic transition. This new demographic syndrome, common in Europe, North America, and Japan, and observed also among urban elites of low-income countries, has been characterized by the postponement of marriage age (even into the 30s), much reduced marriage rates, and fertility falling far below the replacement level. Average US fertility declined from about 3.3 in 1950 to about 2 by the century's end, with analogical decreases from about 3 to 1.3 in Japan and from about 2.9 also to 1.3 in Russia. Although both Japan and Russia have since experienced slight rebounds, they still remain far below the replacement TFR, with Russia recently at 1.75, Japan at 1.5 ([World Bank 2019](#)).

But there have been notable exceptions: French fertility sank close to 1.7 during the early 1990s, but it has been very close to the replacement since 2006 (2.01 in 2015), while the Scandinavian rates never sank as low as in other parts of the continent (Sweden's was 1.88 and Norway's 1.85 in 2015). And French fertility data also illustrate an important decline of fertility toward the end of reproductive age. Age-specific fertilities in 1900 were 1.6 for women of less than 30 years old and 0.6 for those older than 35 years, while by the late 1980s the analogical rates were down to 1.4 and to just 0.15, the latter value being just a quarter of the 1900 rate ([Toulemon 1988](#)).

In contrast, during the 1990s a number of European countries began to record what [Kohler et al. \(2002\)](#) called the lowest-low fertility (TFR<1.3). By 2003 there were 21 countries with such very low fertilities but this new trend was unexpectedly reversed: by 2008 there were only five countries below that level, four of them in East Asia, and while the reversal was particularly vigorous in Europe, it affected all affluent countries ([Goldstein et al. 2009](#)). But that rebound proved short lived: by 2017 TFR at or below 1.3 was recorded in seven European countries, including three major ones (Italy, Spain, and Romania) as well as Bosnia and Herzegovina, Greece,

Moldova, and Lichtenstein, while five nations (including Poland and Portugal) had TFR at just 1.4. Pro-natalist measures have had a poor record, but they have better prospects in countries with TFR still very close to the replacement level.

Thanks to more reliable post-WWII data, we can trace the progress of demographic transition by looking at cumulative shares of the world population. During the early 1950s, two-fifths of humanity lived in countries with $TFR > 6$ and the mean TFR was about 5; by the late 1970s countries with $TFR > 6$ accounted for just 15% of the world population (and the mean fell to about 4.5), and during the first years of the 21st century, just 5% of humanity lived in countries with $TFR > 6$ as the mean rate fell to 2.6. Two generations ago, in the early 1970s, half of all countries had $TFR > 5.5$. During the period 2010–2015, the median value was just 2.3 and only about 50 countries had relatively high fertilities (> 3.5), two-thirds of them classified as economically the least developed ([UN 2017a](#)).

Above-replacement fertility will account for nearly 90% of population growth in Africa, where it will add more than 900 million people by 2050, while in all other regions the rate is expected to either remain below the replacement level or to reach it. That process is already far advanced: by 2015 the accelerating fertility transition has brought more than 80 countries with nearly half of the world's population below the replacement level, compared to about 15% in 1975 and to less than 1% in 1950. Perhaps the most remarkable fact is that by 2018 five of the world's 10 most populous countries had TFR at or below the replacement level (China, United States, Brazil, Bangladesh, and Russia) while India, Indonesia, and Mexico were very close to it, leaving only Pakistan and Nigeria with high TFR ([UN 2017a](#)).

Except for Afghanistan and Timor-Leste all countries with high TFR are in Africa, and in some of them the transition is now well under way. Substantial ($> 30\%$) fertility declines took place in such populous countries as Ghana and Kenya (to, respectively, 4.03 and 4.56), while the shifts were very slow (on the order of 10% or less) in Benin, Burkina Faso, and Malawi ([Johnson et al. 2011](#)). At the same time, the latest assessments show that (for deep-seated cultural and kinship reasons) most African societies still harbor resistance (not evident in other major regions) to lowering fertilities below moderate levels: that is, $TFR < 4$ ([Casterline and Bongaarts 2017](#)).

Since the beginning of the 21st century about 30 European and Asian countries with below-replacement fertilities have seen modest fertility increases, but none of those has been large enough to return such populations even to the replacement level. This partial bounce-back is likely to be repeated in countries whose average fertility has just recently dipped below the replacement level but it, too, is unlikely to bring the return to notable population growth. Further expectations of worldwide fertility decline should put about 70% of humanity below the replacement level by 2050. The speed of this global transition has been one of the most remarkable, and for a long time largely unanticipated, events of modern history, with a wide range of consequences on levels ranging from individual and familial to national and global—but the driving forces of this epochal shift cannot be reduced to just a few obvious factors.

Explaining demographic transition

Search for the causes of demographic transitions has proceeded both along particularistic and synergetic lines but, as already noted in the opening chapter, it failed to produce an explanation consisting of a few quantifiable parameters. The first group of explanations has been dominated by closer looks at reduction in mortality and by changed economics of childbearing (tying it to economic growth theory), with perhaps less attention given to cultural factors (notably to fertility decline as a part of broader emancipation process) and to specific historical exigencies. Decline in infant and childhood mortality—resulting from better sanitation (cleaner water supply, urban sewers), better nutrition (more protein, adequate vitamins and minerals in early diets), better public health measures (vaccination, starting with smallpox) and improved housing—is clearly the most obvious explanation, as it reduces the need to conceive a larger number of children in order to assure that at least one will survive.

Tim Dyson attributed the dominant and universal role to the massive mortality decline, the fundamental remote force whose operation at what he terms the “super-macro” level had eventually caused sustained birth rate declines ([Dyson 2001](#)). No society could endure the perpetuation of falling mortalities and high fertilities for many generations: such a combination would bring so many hardships (ranging from overcrowding and land fragmentation to unemployment and pollution) that before too long a new

approximate equilibrium must be restored and that becomes possible only through reduced fertility.

[Canning's \(2011\)](#) rejection of Dyson's argument that this decline proceeded independently is confirmed by analysis of Dutch historical data. Childhood survival had clear effects on the chances of families having another child and on the length of the intervals between births. This effect, however, was especially strong after 1900 and it was stronger in families of skilled workers than among farm families, and the number of surviving children had different consequences among Liberal Protestant couples, compared to Orthodox Protestant and Catholic couples ([Van Poppel et al. 2012](#)). This historical evidence indicates multiple paths to lower fertility even in a single country, as the reactions to the number of surviving children were determined by how people perceived their lives, how they thought about long-term goals, and to what extent they were willing to achieve them.

Decline in mortality has always preceded the decline in fertility, but in many instances, fertility rose briefly once mortality had begun to fall. And while increased survival obviously reduces fertility needed to ensure a desired number of children, a quantity-quality trade-off (fewer children but higher investment per child) provides a convincing alternative explanation. And in some countries (notably in China and India) modern contraceptives reduced fertility well before the populations experienced higher incomes. And [Conley et al. \(2007\)](#) showed that continued high child mortality is by far the most important factor explaining Africa's high fertility. Farm productivity ranked second, while neither female literacy nor aggregate income seemed to matter as much: "This is where the theory of the demographic transition started: save the children and families will choose to have fewer children" ([Conley et al. 2007](#), 31). This theory also indicates the potential for a relatively rapid fertility transition because the experience from other regions indicates that child survival can be dramatically increased in short periods of time.

According to another hypothesis, the timing of the fertility decline and the number of surviving children should relate inversely to per capita income in countries with similar social and cultural conditions—but (as already noted) neither was true in Europe. Closer investigation shows that there were also notable intra-national differences, and disparities were sometimes seen even among neighboring areas of the same region. In Italy

Sardinia experienced the country's slowest transition, with better-off families being the first to practice deliberate marital fertility control ([Breschi et al. 2014](#)).

Oded Galor related the fertility decline to the gradual rise in demand for human capital ([Galor 2011b](#)). This shift took place during the latter half of the 19th century (during the second phase of industrialization) and it induced households to invest more in their children (creating the human capital), leading inexorably to lower fertilities. Rising incomes first provided greater resources, allowing a larger number of children basic education, and further technical progress increased the return to human capital and led to better average education, reductions in fertility, and declining population growth. This was a self-reinforcing process: as the share of better-educated population increased, technical and organizational progress accelerated and created additional demand for better-educated workers, leading to even higher educational expectations.

Similarly, [Mateos-Planas \(2002\)](#) looked at three major factors that are commonly seen as shaping the transition—mortality decline, technical progress, and the evolution of the cost of children—and concluded that in Sweden, England, and France the contribution of the first factor, although often seen as the most decisive trigger, was limited and that a major part of the shift must be attributed to technical advances and to the changing cost of children. And the rise in demand for human capital also led to higher participation of women in the labor force and to a reduced gender wage gap. Inexorably, this consequence had to contribute to lower fertility: nearly two centuries of the US data show a strong inverse relationship between the female/male earnings ratio and average fertility.

John [Caldwell \(2006\)](#) restated the economic explanation by positing a shift in intergenerational wealth flows: in premodern societies with extended families, the shift was from younger to older generations; in nuclear families, it is from parents to children. Setting aside the most rational economic response to this shift (being childless), the response is to reduce the number of children and cherish them for personal and social reasons, not as economic assets. Yet another common explanation sees high fertility as a form of old-age security. In the absence of pensions and capital markets, children are an asset that can provide support in old age. Establishment of capital markets and pensions for urban workers reduces the need for bringing up more children. Yet this need may have been only a

minor component in the transition, since some arrangements (the English Poor Law Act of 1601) to support old people long predated the onset of demographic transition, and since wealthier families, for whom old-age support is much less of a concern, often had more surviving children.

All of these explanations describe mechanisms dependent on adjustment or adaptation to shifting conditions, while another category of explanations focuses on the importance of the diffusion of relevant innovations. Availability, cost, and effectiveness of contraception is the most obvious example of this effect, particularly when enabled by government policies. Countries with strong support for family planning programs reduced their fertility much faster than those for which government support was absent. At the same time, as already noted in the first chapter, “the data do not support the claim that ‘development is the best contraception.’ . . . They can be used to make a strong case that ‘contraception is the best development stimulus’” (O’Sullivan 2013, 1).

Some demographers and historians preferred to explain the transition by concentrating on cultural factors and on shifts in dominant ideas of personal development: decline of traditional religiosity and secularization of Western societies had to play their parts, as did the quest for greater freedom of choice, the quest for greater personal autonomy and self-realization and, prominently, emancipation of women, their pursuit of independent careers, and the associated cost of requisite child care. That is why [Lesthaeghe \(2014\)](#) concludes that declining fertility is a part of a broader emancipation process motivated by the quest for the attainment of individual goals. Demographic transitions have no single triggers and national experiences do not repeat an orderly preordained sequence. Outlining the consequences of demographic transitions is much easier, and some of those impacts have amounted to the most fundamental transformations of modern civilization, none more so than the rapid multiplication of global population.

Consequences of demographic transition

The focus should start with the profound effects the process has had on the lives of children and families. Reduced suffering and pain have been the most consequential improvements for newborns, children, and their parents. The transformation of infant mortality from a high-probability event to a rare misfortune accounts for most of these gains. In affluent countries with

the best preventive and postnatal health care, infant mortalities have been reduced to just 2 or 3 per 1,000 live births: just two families out of a thousand have to experience what every third family went through (and often repeatedly) two centuries ago. The global mean is still an order of magnitude higher (30/1,000 in 2018) and the rate is twice as high in the world's poorest nations.

Another, and usually ignored, benefit has been an (albeit temporary) increase in family stability. Dutch data show convincingly how the transition affected the living arrangements of children. Because of the combination of declining adult mortality, lower out-of-wedlock fertility, and relatively low divorce rates, more children born between 1880 and 1964 lived in complete families than at any other time in history ([Van Poppel et al. 2013](#)). Subsequently, the trend began to reverse, and growing up without a father (or stepfather) became more common in cohorts born after the 1980s than it was during the 19th century.

Reduced infant and childhood mortality normally confers lifelong benefits of more parental attention and more material resources devoted to a child's upbringing. Analyses focusing on educational attainment among adults and plans for getting post-secondary education among adolescents support the expectation of the "dilution model" on the quality of children even in the affluent United States. Moreover, these analyses indicated that children without siblings did not suffer in their development. On the other hand, recent evidence from China, where the forced one-child policy created large cohorts of single sons and daughters in conjunction with rising family wealth, points to higher frequencies of such undesirable traits as childhood obesity.

And, of course, having fewer children means higher average living standards for smaller families, with more opportunities for better housing, higher-quality nutrition, more frequent travel, and higher retirement savings. Widely admired economic advances of East Asian countries (starting with Japan, followed by Taiwan, Singapore, South Korea, and Malaysia and, since the 1990s by China and Vietnam) could not have been translated into rapidly rising per capita incomes, family wealth, and better overall quality of life had their fertilities remained at pre-transition levels (Japan ~3, Korea and China ~6).

In physical terms, improved quality of population has been expressed most obviously by increasing heights, in social terms by general access to

basic education and by improved status of women. As malnutrition and stunting were eliminated, average heights for every age group kept rising (NCD Risk Factor Collaboration 2016). The largest height increments during the 20th century were in Asia. South Korean women gained just over 20 cm on average, and 18-year-old Japanese males were nearly 12 cm taller than their counterparts in 1900 (SB 2006).

Fertility reduction has been a necessary (but not necessarily sufficient) precondition for greater female independence, opportunities for self-realization, and large-scale participation of women in the labor force. This shift started with unskilled jobs in manufacturing and proceeded to skilled jobs in education, health care, and offices, and that shift eventually led to rising relative wages (although complete parity has yet to be achieved in most settings) and in some countries to a very high share of women doctors, lawyers, and politicians. US data show the employment rate rising from 18% in 1890 to 25% by 1930, and 33% by 1950, and peaking at 60% in the year 2000 (rates for single women being about double the overall rate) with a subsequent slight decline to 57% in 2018 (FRED 2018). This trend (by now widely replicated around the world) has further social and economic repercussions ranging from increasing divorce rates to demand for state-supported child care.

Two major outcomes of demographic transition that have affected every aspect of economic and social development as well as the quality of the environment have been the unprecedented growth of human populations and the creation of a demographic dividend engendered by a shifting population structure. The time lag between the falling mortalities and natalities created temporary periods of rapid population growth that brought sequentially faster doublings of global population and led to irrational fears about its uncontrolled expansion. As already noted, our best estimates of prehistoric population growth indicate annual rates well below 0.1%, with doubling times extending to a millennium or more. The global count reached 1 billion people during the first decade of the 19th century after taking about 250 years to double from 500 million; but reaching 2 billion took only 123 years (by 1927).

The next doubling to 4 billion (by 1974) was done in just 47 years, but as the post-1970 growth rate slowed, the unfolding doubling to 8 billion will be accomplished in 52 years, by 2026 (UN 2017b). Reconstructions of global population totals show the average annual growth rate reaching 0.2%

during the late 17th century, surpassing 0.5% before 1820—and then rising to 0.8% by 1910 and to more than 1% by the early 1930s. The rate continued to rise after World War II and André de [Cailleux \(1951\)](#) was the first demographer to note this *surexpansion*—that is, the growth at an ever-increasing rate (hyperbolic function)—and [von Foerster et al. \(1960\)](#) used the pre-1960 growth to calculate that its continuation would reach a point of singularity (infinitely rapid growth) on November 13, 2026.

Of course, there was never any danger of that phenomenon and the hyperbolic expansion ended abruptly. The [World Bank's \(2019\)](#) reconstruction has two annual growth peaks, at 2.107% in 1966 and at 2.109% in 1969, but claiming accuracy to the third decimal place for any number associated with the global population growth is indefensible. What is defensible is to conclude that the peak population growth rate of about 2.1% was an order of magnitude above the rate that prevailed just three centuries earlier. Subsequent decline brought the average annual rate to about 1.3% by the year 2000 and the post-2015 mean has been less than 1.2%. We are nearing the end of yet another doubling, and to reach 8 billion will have taken about 50 years, a clear indicator of declining global growth rates.

The second fundamental consequence of demographic transition has been its impact on economic growth. Has it been restricted or promoted by the unprecedented increase of populations, or has the overall effect been largely neutral? Evidence can be found to support every one of these three effects. A better way to evaluate demographic transition's role in economic growth is by focusing on changing age structures in general, and on the importance of what has become widely known as the demographic dividend in particular. This approach recognizes the enormous impacts of existential requirements and economic behavior at different stages of life.

In the earliest periods of demographic transition, economies have to take care of large cohorts of children, and the diversion of resources to requisite health care and schooling slows down the rate of economic growth. As the transition progresses, a temporary combination of declining fertility and of a growing number of young people reaching adulthood results in a share of economically active people (defined either as 15–64 years or 20–64 years old) significantly higher than the total share of dependents: that is, children below 15 (or children and adolescents below 20) and elderly people above 65 ([Mason et al. 2017](#)). Nations experiencing falling total dependency ratios

benefit from a temporary demographic dividend ([Bloom et al. 2003](#)). This shift may happen rapidly but it provides the strongest stimulus to economic productivity only if the growing cohort of economically active people has benefited from sensible macroeconomic policies (openness to trade, flexible labor markets, encouragement of savings) and only if it had access to adequate nutrition, health care, family planning, and education when growing up.

Average incomes rise, and this rise is reinforced as women (whose childbearing and childrearing commitments kept them previously at home) enter the labor force. Average savings increase, sometimes to 30–40% of disposable income, and provide much of the capital for further economic expansion. Higher disposable incomes create new demand and economies profit from this virtuous cycle. Since the 1950s demographic transition has produced this temporary dividend in many countries in Asia and Latin America. East Asian countries have been its greatest beneficiaries, because their total dependency ratios kept on falling for three or even more than four decades. South Korea's total dependency ratio was declining for 49 years between 1962 and 2011, China's for 37 years (between 1973 and 2010), and Vietnam's for 45 years (since 1968 to 2013). India's overall dependency ratio has been falling since 1966 and it has come close to the Chinese rate ([World Bank 2019](#)). China's remarkably low total dependency ratio has been the legacy of the country's one-child policy, in force between 1979 and 2015. In 2010 the ratio reached its lowest rate at nearly 35, compared to the global mean of about 53.

In contrast, the dividend had a more muted impact in Latin America (largely due to less effective government policies), and major African economies have yet to see these benefits, as their high fertilities have either kept their total dependency ratios from falling (Nigeria's ratio has been steady at close to 90) or as the decline has been only from very high to high ratios (Kenya's rate fell from more than 110 in the early 1980s to less than 80 by 2015). The demographic dividend is inherently time limited but its positive consequences can endure well beyond its end. As the large cohorts of working-age population age and retire, the dividend first recedes and then it disappears, but it can have a longer-term economic effect if the temporary gains were invested in infrastructures, education, health, and technical advances.

The dependency ratio then shifts once more, rising with the increasing share of retired people and forcing countries to deal yet again with growing shares of less-productive (part-time employment among elderly) and nonproductive (retired) segments of the population. This shift could be reversed only by an unlikely return of higher fertilities. In its advanced stages this process is undoubtedly a net burden for any rapidly aging society, but in its early stages, this dividend has been marked by rising wealth relative to income ([Mason 2005](#)).

Consequences of demographic transition are also quite evident when we take closer looks at major stages of economic development. In the transition's early stages, growing cohorts of young people seeking employment favor the establishment of labor-intensive and export-oriented manufactures, the developmental pattern pioneered after World War II by Japan (with its textile, automotive, and electronics industries) and then very successfully replicated in successive iterations in Taiwan (with a wide assortment of consumer goods), South Korea, and China, with all of these three countries greatly benefiting from the global demand for personal and portable electronics.

Further economic benefits have ensued from the improved health and better education of new job seekers who came from smaller families. Universal vaccination, perinatal care, preventive health care, and better nutrition enabled the first improvement, while many countries had eventually extended compulsory education to 18 years of age. Moreover, increased longevity and longer spans of healthy living have lengthened the time for the return for investment in longer schooling. Many highly specialized professionals now enter the labor force only in their late 20s and early 30s, ages that would have left them with just two decades of productive work during the pre-transition era.

Scores of countries are already experiencing the latest stage of demographic transition that will bring a new combination of concerns. Although we cannot pinpoint the eventual global maximum, there is no doubt that an S-shaped growth curve is forming. But even if we were to reach a new plateau very soon (say at 10 billion people), the consequences of the past acceleration in population growth would be with us for a long time, as affluent countries and an increasing number of modernizing economies have to deal with longer life expectancies and some are already seeing population declines. And unprecedented urban expansion,

culminating in the rise of megacities, could not have been accomplished without mass-scale migrations. Consequently, the remainder of this chapter will look at the challenges of aging, population decline, urbanization, and migration.

Life Expectancy, Aging, and Population Decline

Demographic dividend has its obverse in demographic burden, which is imposed on those countries where the fertility falling far below the replacement level results not only in the rise of dependency ratio but also in gradual population decline. Of course, the latter phase has to wait until the relatively large cohorts of women move past their reproductive age: once this population momentum has been spent, populations will start contracting (Keyfitz and Flieger 1971; [Blue and Espenshade 2011](#)). The demographic burden will become much more onerous in societies whose life expectancies will reach record highs on previously unthinkable scales: Japanese population projections foresee octogenarians outnumbering children by the middle of the 21st century (NIPSSR 2017). There was never such a society in some 10,000 generations of *Homo sapiens*, but we already have plenty of evidence concerning the consequences of local and regional population declines from Japan and from parts of Europe.

Extension of life span

Gains in average life span came first from reduced infant mortality and from nearly complete elimination of untimely deaths. Rates in continental Europe and in the United States fell from 200–300 per 1,000 live births in 1850 (with every third to fifth child dying before its first birthday) to just 35–65 a century later, and by the year 2000 the rates in affluent countries were commonly below 5, nearly 50 countries had rates below 10 (1% of infants dying), and only 19 nations (all in Africa) had a rate above 100 (10%), roughly the same as Europe had a century earlier ([Abouharb and Kimball 2007](#)).

Contrary to a common impression, medical advances did not play the primary role in the 19th-century reduction of mortality: improving standards of living, above all better nutrition, better housing, and better

public health measures (water piped in, waste disposal, better household hygiene), were the decisive factors (Fogel [2004](#) and [2012](#)). Early health insurance programs also helped: data for five European countries (including France and Germany) show that between 1873 and 1913 these programs accelerated the downward trend in mortality not only because of expanded health care but also because of dissemination of health information and hygiene awareness (Winegarden and Murray [2004](#)).

As McKeown et al. (1975, 391) found in England and Wales, “therapy made no contribution, and the effect of immunization was restricted to smallpox which accounted for only about one-twentieth of the reduction of the death rate.” McKinlay and McKinlay (1977) extended this finding to the 20th-century United States. They showed substantial post-1900 mortality declines for measles, scarlet fever, tuberculosis, typhoid, pneumonia, and diphtheria before the introduction of specific therapies (vaccination, sulfa drugs, chloramphenicol, penicillin), and concluded that in the case of those illnesses for which mortality had an appreciable decline after the point of intervention, no more than 3.5% of the total post-1900 reduction could be ascribed to medical advances. Polio vaccination (introduced in 1955) was the only measure that brought a notable change of a trend. Overall, America’s age-adjusted mortality declined by 74% during the 20th century, and 70% of that drop took place before 1950, thanks largely to a decrease in infectious-disease mortality (Singh and van Dyck [2010](#)).

Before the discovery of sulfa drugs in the 1930s we had nothing to suppress the most common infectious diseases and Jayachandran et al. (2010) found that between 1937 and 1943 the use of these new medications brought a 25% decline in America’s maternal mortality, a 13% decline in pneumonia and influenza mortality, and a 52% decline in scarlet fever mortality. This conclusion does not invalidate the wider claim about the decisive role of better hygiene and better nutrition that made such a difference in reducing infant and childhood mortality.

As a result, until the mid-20th century less than 20% of overall longevity gains were realized in those older than 65 years of age; that ratio has been reversed, with more than 75% of the gains in life expectancy taking place among elderly people over 65 and, moreover, that share is rising as it is approaching its asymptote (Eggleston and Fuchs [2012](#)). This longevity transition is still in its early stages for most of humanity. Advances in prevention and treatment of diseases that account for most adult mortality

(cardiovascular events and cancers) are available only to urban elites in the world's poorest populous nations in Asia and Africa and as a result this new demographic transition will be with us for the entire 21st century.

Historical trajectories of this process can be best outlined by tracing the gains in average life expectancy at birth. This statistical construct merely indicates the average number of years a newborn child is expected to live if mortality patterns prevailing at the time of its birth remain constant in the future, and it might be the best single-variable indicator of overall quality of life. Much like the other telling indicator, infant mortality, life expectancy is predicated on the combination of good health care, good nutrition, and good living conditions, but all of these must endure for decades, not just for the first year of life.

Between 1850 and 2000, the highest life expectancies in Western Europe, North America, and Japan followed linear gains as their averages for both sexes doubled from about 40 to almost 80 years, while the longest female life spans (women live longer in all societies) had surpassed 80 years. During the 20th century, the gain in most high-income countries was about 30 years ([Marck et al. 2017](#)). In global terms, World War I (1914–1918) with the overlapping influenza pandemic (1918–1919) and World War II (1939–1945) were the only two periods of temporary reversals in average life expectancy at birth. Japanese women have been global record holders for decades, and by 2010 their average life expectancy at birth had surpassed 85 years (SB 2017).

In 2015 the top dozen countries for the combined (male and female) longevity at birth were Japan, Switzerland, Singapore, Australia, Spain, Italy, Iceland, Israel, France, Sweden, South Korea, and Canada ([WHO 2018a](#)). Differences at the top are marginal: Japan 83.7, Switzerland 83.4, France 82.4, and Canada 82.2. The same is true when we compare an even more revealing indicator of healthy life expectancy defined as the average number of years that a person can expect to live in “full health”: Japan (again, combined for both sexes) leads with 21.1 years of healthy life beyond the age of 60, thanks to the exceptional longevity of its women (23.1 years), but at 19.9 years the second, Switzerland, is barely above the 12th, Canada (19.7 years).

This group of longevity leaders clearly indicates that the highest per capita economic product and the highest life expectancy are poorly correlated: only 2 of the 12 longevity leaders (Singapore and Switzerland)

rank among the 12 countries with the highest per capita GDP (expressed in purchasing power parities), and 7 of the 12 longevity leaders do not place even among the 25 richest countries ([World Life Expectancy 2018](#)). At first glance, a balmy climate (Australia, Spain, Italy, and Israel) might seem to be a factor, but just as many leaders (Switzerland, Iceland, South Korea, and Canada) negate that conclusion. Longevity is an outcome of complex interactions that include economic, nutritional, and health care variables, and recent research indicates that attitude to life is another key attribute shared by the longest-living individuals: those with more positive self-perception of aging lived up to 7.5 years longer than those with a less positive outlook ([Levy et al. 2002](#)).

In contrast, at the bottom of the ranking, the correlation with economic misery accompanied by poor nutrition and often absent health care is obvious: all 20 countries with life expectancies below 60 years are in sub-Saharan Africa. And the link between the progress of the demographic transition and life expectancy is equally obvious: those sub-Saharan countries that have either barely embarked on the shift or that are in its earliest stages are also the ones with the shortest life spans. The exchange of quantity of human lives for their quality (fewer children but more of them surviving and living longer) is obvious.

A new, and unexpected, reverse phenomenon was first noted in the United States during the early 21st century: after generations of steady decline, mid-life mortality among white non-university educated population stopped falling and it began to rise ([Case and Deaton 2020](#)). Will these “deaths of despair” (largely attributable to suicide, drug overdose, and alcohol-induced liver disease) remain an American oddity or will they affect future life expectancy in other de-industrializing countries?

Demographers and physiologists have been divided about further prospects for longer life expectancies. Aging is an irreversible process following an exponential decline that begins already in the third decade of life and from which we still see no effective escape ([Marck et al. 2017](#)). Not surprisingly, the preponderance of evidence indicates that additional gains in maximum life expectancy will be limited. The longest-ranging data (from the 1820s to the beginning of the 21st century) for Sweden, France, and the United Kingdom show nearly doubled life expectancies at birth but their progression conforms closely to logistic curves whose growth began to decline in the 1920s and whose post-2000 gains appear to be limited to just

one more year by 2050 ([Zijdeman and de Silva 2014](#); Smil 2019a). Another confirmation of limits comes from a study of supercentenarians in France, Japan, the United States, and the United Kingdom ([Dong et al. 2016](#)).

Between the 1970s and the early 1990s, the largest increases in survival were seen in ever-older age groups, indicating that there is no imminent limit to the maximum longevity—but then the gains plateaued at just short of 100 years, and since 1997, when Jeanne Calment died at 122.4 years of age, nobody has outlived her. If some considerable doubts about her record ([Zak 2018](#)) get confirmed, then the oldest verifiably recorded age is 119.26 years (Sarah Knauss). And yet another proof that we are already very close to the maximum comes from detailed American statistics. The nation's incremental gain for both sexes averaged 152 days/year between 1900 and 1950, when the mean at birth rose from 47.3 to 68.2 years—but only 63 days/year between 1950 and 2000, when the average reached 76.8 years (CDC 2011). This progression conforms to a logistic curve with an asymptote just short of 80 years by 2050. Longevity gains for females have slowed down even faster, from 166 days/year during the first half of the 20th century to just 60 days/years during the next 50 years.

Human life span thus appears to be fixed, not necessarily because of a genetically programmed maximum but because of a combination of natural constraints ranging from chronic diseases to the biomechanical limits of proteins (including the ubiquitous elastin) that form internal organs, bones, and muscles ([Robert et al. 2008](#); [Olshansky 2016](#)). The highest national means of female life expectancies might rise to, or even a bit above, 90 years during the next two generations; it is most unlikely that the means for both sexes would come close to 100 even late in the 21st century or that many people will live longer than 115–120 years. Yet another confirmation comes from the studies of Olympian and elite athletes: with maxima at 106 years this highly selected group has life spans six to seven years longer than the general population (Antero-Jacquemin et al. 2014). But its longevity gains also show clear saturation: more and more individuals may be approaching the limit without surpassing it.

There are slightly more optimistic assessments. A study that decomposed life expectancies in 16 high-income countries into juvenile, adult, and senescent components found the combined (female and male) senescent expectancy improving by 0.15 years (55 days) per year and concluded that such a gain might last for a few more decades ([Bongaarts 2006](#)). And

because recent Japanese female life expectancies have already surpassed some previously forecast maxima, [Oeppen and Vaupel \(2002\)](#) envisaged additional substantial gains. And I should note that there are those who believe that we will be eventually able to rejuvenate human cells by extending the fraying telomeres or by prolonging life by restricted energy intake, but so far neither of these effects has been demonstrated in humans ([Jaskelioff et al. 2011](#); [Mattison et al. 2012](#)).

Aging societies

Prospects of higher longevity are good news for those individuals who will age relatively uneventfully (remaining fairly ambulant and mentally competent) as they can look forward to additional years of life—but this benefit has to be balanced by the realities of prolonged suffering of many individuals whose aging will be accompanied by increasing frailty and often by many concurrent mental and physical impairments that pose familial, social, and financial challenges. These demands will be particularly onerous in societies whose very low fertilities have not been producing adequate numbers of potential caregivers, with Japan providing the leading example of this burden.

In 1985 only 10% of Japanese were older than 65, but that share had doubled by 2007, and by 2015 nearly 27% of all Japanese were older than 65 years of age (SB 2006 and 2017), a share not only higher than in countries with large-scale immigration such as the United States (14%) and Canada (16%) but also higher than in such aging European nations as France (19%) and Germany (21%). And the Japanese share of people older than 65 is expected to rise to 30% by 2030 and to 33% by 2036, and in some prefectures (including Fukushima and Iwate, affected by the March 11, 2011, earthquake, tsunami, and nuclear disaster) nearly 40% of all people will be 65 years and older by 2040 (NIPSSR 2017).

Japan's old-age dependency ratio rose from about 9 in 1950 to 11 in 1975. It was 25 in the year 2000 and nearly 44 in 2015, but it will rise to nearly 73 by 2030 and to almost 75 in 2065 (NIPSSR 2017). This increase means that already by 2030 there will be just 1.36 people of working age for every old person, compared to 4 as recently as the beginning of the 21st century! The most practical step to make this situation less onerous would

be to raise the retirement age to 69 and thus bring the number of economically active people closer to 2 people per retiree.

Even more challenging will be the increase of people in the oldest cohorts, and we still have no clear idea how such geriatric societies will function. The financial burdens of increased welfare costs and health expenditures have been assessed by many recent studies ([Bloom et al. 2003](#); [Lee and Mason 2011](#); [Oshio and Oguro 2013](#); [Hara 2015](#); GOS 2016). Slowdown of overall output is roughly proportional to declines in the labor force and population growth, and aging will strain even the best-designed pension schemes. Moreover, it comes on top of already high reliance on public-sector transfers (particularly in the EU countries), common government budget deficits (the European Union's average debt/GDP ratio is about 82%, the US rate is 105%, and Japan's record level is at 250% [[Trading Economics 2018](#)]), and the low attractiveness of jobs in elderly care.

Since the year 2000 Japan has had a universal long-term-care insurance system that should cover all medical needs and social services for people above 65 on the basis of their needs and regardless of their economic status ([Muramatsu and Akiyama 2011](#))—but this promise is obviously predicated on adequate funding and availability of health care and social workers, and countries with aging populations are already facing shortages of care personnel, particularly in rural depopulating regions. The prospect is made worse by large increases of old people who live alone: in Japan that share has quintupled since 1960. At the same time, it would be naive to believe that the recent claims about the advances in AI, robotics, and assistive engineering designs (robots lifting bedridden patients, keeping company, and watching mental patients) will largely eliminate the need for human care in aging societies.

Japanese media have been reporting on unprecedented numbers of demented people and increasing frequency of *kodokushi*, lonely death with bodies remaining undiscovered in apartments for relatively long periods of time ([Allison 2013](#)). But some adjustments are already under way: in some municipalities, those worried about dying alone can now sign contracts with funeral homes that will arrange for regular visits by city officials and that will eventually take care of their funerals and their postmortem affairs ([Kyodo 2018](#)). Recent studies also give us new insights into the prevalence

and progression of frailty characterized by shrinking body mass, exhaustion, low activity, slowness, and weakness.

A comprehensive assessment of people aged 65–91 found the respective prevalence of these conditions to be about 10%, 39%, 21% 11%, and 16% but the prevalence of pre-frailty (with limitations in one or two of the five of the previously mentioned characteristics) was 52% ([Yuki et al. 2016](#)). These findings correspond to 2015 populations of about three million frail people requiring care and of nearly 18 million people in the pre-frailty stage. And a systematic meta-analysis of the prevalence of frailty in Japan uncovered the extent of its inexorable rise with aging, from only about 2% among those between 65 and 69 years old to 4% for those between 70 and 74, 10% for those between 75 and 79, 20% for people in their early 80s, and 35% for people older than 85 years ([Kojima et al. 2017](#)). Another recent finding is that, unlike in women, living alone has been significantly associated with frailty in old men ([Yamanashi et al. 2015](#)).

At the extreme, living to 100 has been always seen as an admirable achievement but it is also a highly problematic one. Japan has the world's largest number of centenarians, with new records set every year. By the end of 2017, it was about 68,000 and the forecast for 2050 is about 41 people of 100 years and older for every 10,000 inhabitants, bringing the total of centenarians to more than 400,000. But a study of their functional status showed that the health of only 18% of them could be classified as normal for their age, while 55% were frail (either mentally or physically compromised) and 25% were fragile, with both cognition and physical capabilities deteriorating ([Gondo and Poon 2007](#)). Multiply these shares by more than 400,000 centenarians and Japan's mid-21st-century elder-care challenges become daunting indeed.

Aging will make yet another challenge more complicated and more onerous: rescue and care of old people in the case of major natural disasters. Again, Japan has provided some early insights into the possible extent of this problem. The magnitude 9.0 Tohoku earthquake of March 11, 2011, affected one of Japan's poorest, depopulating regions and provided a tragic preview of what might happen in any heavily populated area where large numbers of elderly people would be left without access to medications and exposed to cold, heat, infections, stress, and general loss of security. In the Tohoku earthquake's aftermath, the latter reality has been the most consequential ([Hasegawa 2013](#)).

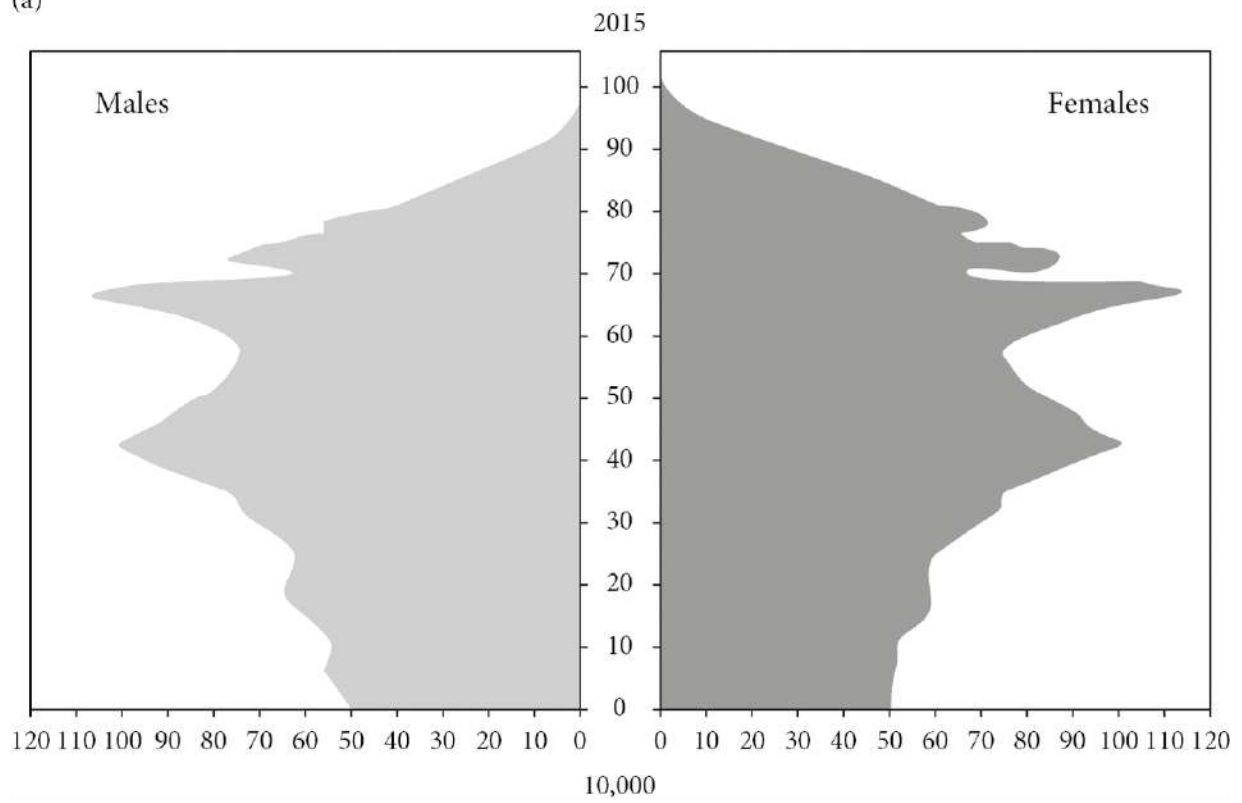
Very few people died of any immediate post-quake neglect, but six years after the accident some 134,000 people, resettled in nearby towns or in the high-rises of Japan's largest cities, remained displaced ([Yonetani 2017](#)). This loss of home has been particularly difficult for elderly people whose families lived in the region for generations or those who chose the area for affordable retirement. Studies found that these old people face continued uncertainty and experience hopelessness and helplessness as they live isolated in allotted housing far away from their contaminated homes ([Okamoto 2016](#)).

Declining populations

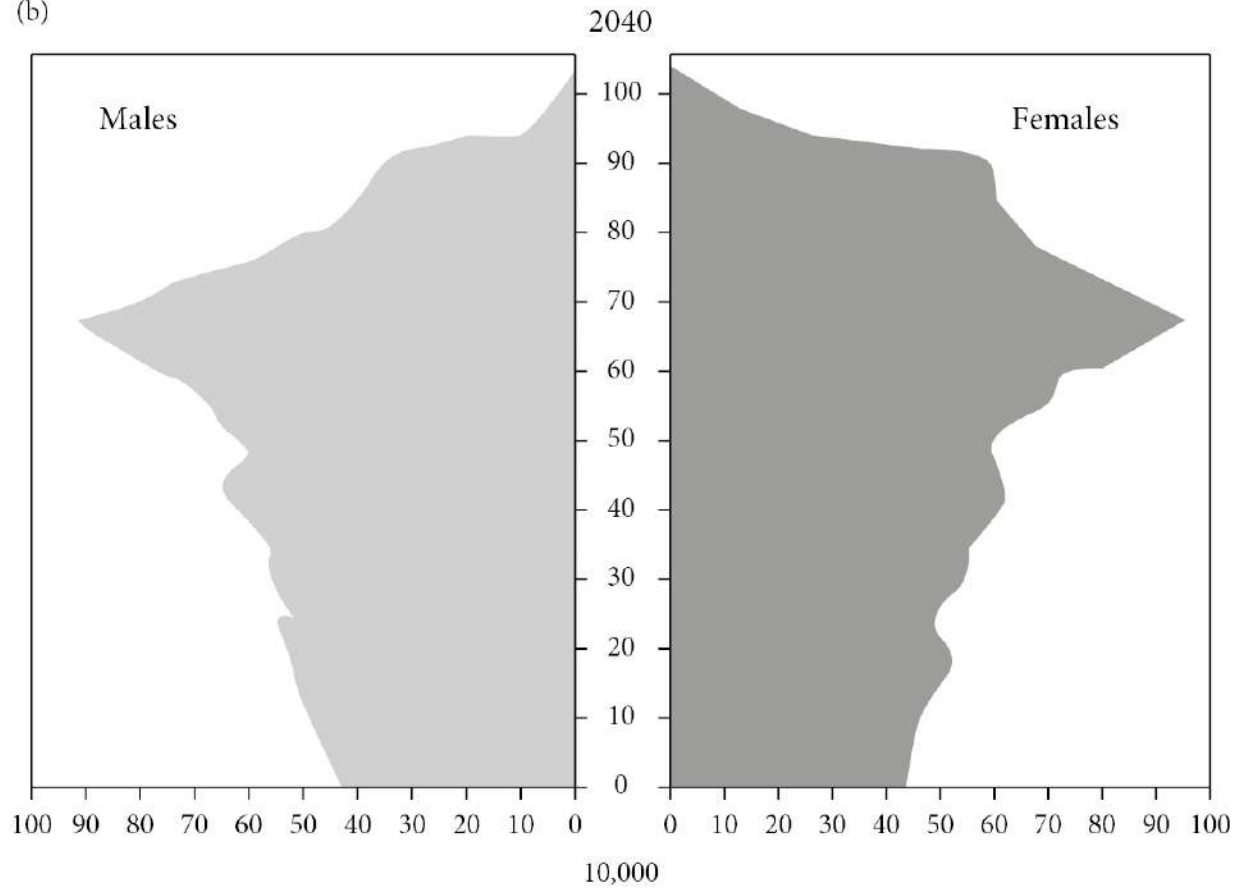
Moreover, Japan's aging trend has been accompanied by perhaps an even more challenging development, as the country is now experiencing significant population losses ([Hara 2015](#)). The first decline (even after including net migration) was in 2005, the second one was in 2009, and uninterrupted losses began in 2011, with a natural population drop reaching nearly 300,000 people in 2016 (SB 2017) and setting a new record loss of 512,000 people in 2019 ([Kyodo 2019](#)).

The medium variant of the latest quinquennial NIPSSR forecast (combining medium fertility and medium mortality) sees the population falling from 127 million in 2019 to below 100 million by 2053 and the total declining to about 88 million by 2065, when people 65 years and older should make up more than 38% of the country's population and their total would be about 3.8 times larger than that of children; analogical figures for the low-fertility projection would be about 82 million, just over 41% and 4.9 (NIPSSR 2017). Comparison of age-and-sex structures for 2015, 2040, and 2065 makes this process clear at a single glance ([Figure 2.4a–c](#)). In neither case could they be called (as has been common in the past) pyramids, because even in 2015 the base was less narrow than the middle.

(a)



(b)



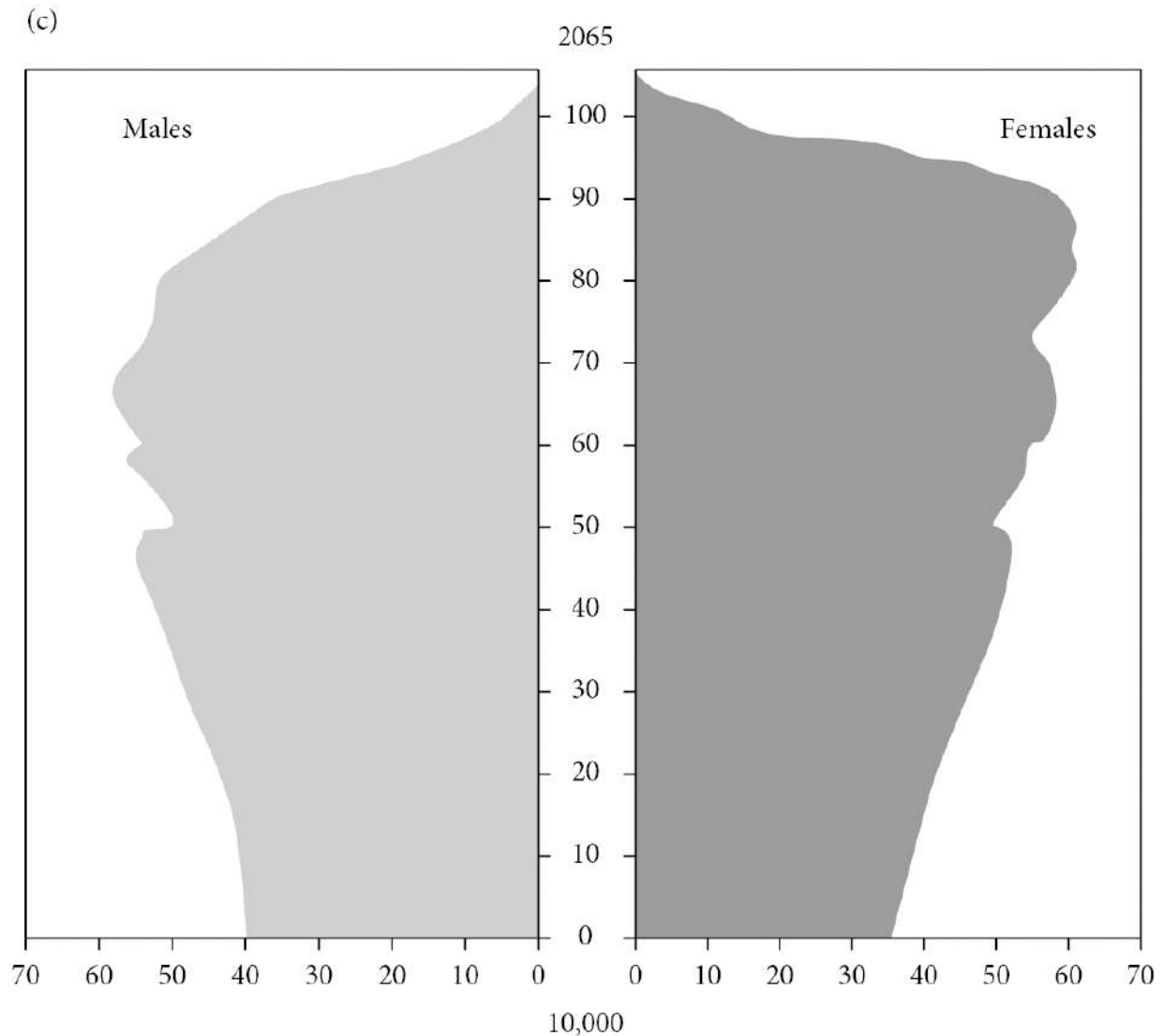


Figure 2.4 a–c Age-sex distribution in Japan in 2015 and its medium-fertility variant projections for 2040 and 2065: the country is expected to have nearly four times as many elderly people (65 years and above) than children (0–14 years), and more than twice as many people in their 80s as children younger than 10 years. Such age distribution would be unprecedented. Plotted from data in NIPSSR (2017).

Inevitably, the loss of up to 45 million people in 50 years (the total almost equal to the population of Spain) will have many consequences. Depopulation has been affecting many rural areas for decades. As many villages cease to be functional units, the advancing depopulation forces their abandonment and the consolidation of essential services to more viable localities—but even these two efforts are just a delaying action: by 2040 nearly 900 towns and villages will not be viable ([Nikkei 2014](#)).

Depopulation of villages has already reached a worrisome extent in some poor mountainous areas and on small islands, and the accelerate trend will also lead to mass-scale abandonment of numerous small towns. Iwate, Honshu's northernmost prefecture, is projected to lose 35% of its population by the mid-2030s; Fukushima prefecture should shrink by about 30% ([Hara 2015](#)). The total area of unclaimed land was already 4.1 million ha in 2017, and it is expected to reach 7.2 million ha by 2040, nearly four times as large as the entire island of Shikoku ([Kyodo 2017](#)). By 2018 the number of vacant houses (increasingly also found in the capital, whose population still keeps growing) has surpassed 10 million.

These population losses will further undermine the already weakened position of Japan as one of the world's leading manufacturing economies, and the country's political standing will be surely affected by the fact that by 2060 there might be more Turks or Vietnamese than Japanese. At the same time, there is no obvious link between a country's (or a city state's) population total and its importance. This disparity holds both historically (ancient Greece, Venice) and in recent decades when the economic and political influence of such small states as Taiwan, Singapore, and Israel, and such mid-size countries as Canada and South Korea, have been relatively much larger than their population size: in 2019 Canada was the world's tenth largest economy although its population ranked only 38th.

Japan's modern history is itself a source of such comparisons: in 1905, when Japan defeated imperial Russia, it had only 47 million people, compared to Russia's 135 million; and during the 1960s, when the country emerged as a new manufacturing superpower, the population was around 100 million. Japan of some 90 million people in 2060 would have a population as large as it did in 1955, just a year after its GDP surpassed its pre-WWII peak and when the country began its impressive economic rise. Japan of the mid-21st century will remain among the leading contributors to global technical and social development, and it has the option to prevent any population decline by turning to sustained, mass-scale (Australian- or Canadian-style) immigration. So far, it has shown only a very limited willingness to take migrants from neighboring countries.

The conversion of China's demographic dividend to demographic burden will proceed even faster: in 2015 slightly less than 10% of the country's people were older than 65, but by 2050 that share will surpass 26%, growing nearly threefold compared to Japan's increase of some 40% during

the same period. Burdens of population aging are already evident in China, as the state has to deal with rising shortfalls in the country's inadequate pension funds. Chinese aging will be also affected by the world's most extreme gender imbalance, created by the selective abortion of girls during the decades of the one-child policy. As a result, millions of Chinese men will never find a partner, and as they come mostly from single-child families, they will die alone.

The transition to a geriatric society in Japan is notable because the country is already so far ahead along this trajectory, and in China because there the process is affecting a population that is an order of magnitude larger. But in the long run and in the global perspective, neither country is unique, because both pronounced aging and absolute population declines are already common in parts of Europe. Aging affects other Asian countries (South Korea and Taiwan being the most prominent examples), and the United States and Canada keep the transition at bay only by resorting to mass-scale immigration, a process with its own problems.

Migrations and Urbanization

Growth of cities through migration is as old as settled civilization itself, but during the premodern era both the intensity and the extent of this transition were limited. All but a small fraction (typically less than 10%) of national or regional populations continued to live in villages, most larger settlements were just small towns rather than cities (there is no clear statistical division between the two, with national definitions differing by as much as an order of magnitude), and large cities were rare exceptions ([UN 2016](#)). Around 7000 BCE Neolithic Çatalhöyük in Turkey housed about 1,000 people; 6,000 years ago Sumerian Uruk had a population of 5,000 ([Davis 1955](#); Çatalhöyük Research Project 2018).

The largest Mesopotamian cities grew later to several tens of thousands of people, and the population of classical Athens reached some 40,000 ([Morris 2005](#)). Estimates for Alexandria range from 500,000 to 800,000 and for imperial Rome from 800,000 to one million. But these were exceptions, as the size of premodern cities was limited by crop yields and by land transportation capacities to deliver food, fuel, and construction materials. The largest cities of antiquity and the Middle Ages were those accessible by

shipping, with Rome receiving waterborne transport as cargos arriving at Ostia were reloaded on shallow boats and dragged against the Tiber's current to the city.

Baghdad was the only medieval city whose population could have reached one million by the 10th century, while Europe's largest medieval cities—Paris, Milan, and Genoa—had between 100,000 and 200,000 people, Hangzhou and Beijing reached 400,000, and Cairo had perhaps as many as 600,000. Beijing, capital of the Ming and Qing dynasties, was the largest city until the 18th century, but by 1800 both Tokugawa Edo (now Tokyo) and London matched its size of one million inhabitants. American cities of the early 19th century were small: in 1800 New York had just 65,000 people, Boston about 25,000. Cities in cold climates faced an additional limitation because they also had to secure adequate fuel for seasonal heating.

Urbanization is a prime example of the interactive nature of grand transitions. Mass-scale movement of people from the countryside to cities could not have taken place without the agricultural transition that allowed the rural labor surpluses to migrate to cities. The cities could not have sustained high rates of growth without both agricultural and energy transitions that were able to supply food, thanks first to railways and then to new global markets for crops and meat (including refrigerated shipments since the late 1870s) and fuels and electricity, enabling unprecedented urban power densities. And the urban-led economic transition created new mass-scale opportunities in manufacturing and services that acted as the pull force for rural emigration and that provided new and affordable inputs of machines, devices, and processes needed to sustain and to expand both agricultural and energy transitions.

The expanding reach of cities beyond their immediate hinterlands and their demand for food, energy, and materials had eventually extended worldwide, and urban areas became the most prominent generators of local and regional environmental pollution. The environmental burdens of pre-transition towns and cities (smoke from inefficient combustion of wood; absence of sewers; contaminated water supply; animal-drawn transportation; extreme crowding; lack of greenery) were transformed by urban modernization and redesign—only to create new burdens within the cities and far beyond their expanding boundaries.

New types of air pollution have included particulate matter and sulfur oxides from the combustion of coal and from the growing automobile traffic generating photochemical smog; its first episodes were observed in the 1940s in Los Angeles, and since the 1960s it has become a common seasonal affair in most of the world's largest cities. Additional air pollution has come from metallurgy and petrochemicals. Urban water pollution was common during the early stages of industrialization and growing material consumption. Food waste and the demolition of old housing have been the leading non-industrial sources of solid waste: its treatment ranges from abandonment and illegal dumping to burial in landfills, incineration, and export to distant locations. And many large cities are particularly vulnerable to sea-level rise because of their coastal or low-elevation locations (four out of every five of China's largest cities are so located).

Crowding, so characteristic of early industrial cities, was relieved in many European countries after World War II, but not in the slums of Asia and Latin America. All cities began to impose larger footprints on the environment: incessant inputs of food, energy, and materials are often supplied most conveniently by shipping from distant locations rather than by imports from urban hinterlands, extending the urban-driven environmental degradation to croplands, forests, and grasslands on all continents, and with their industries and transportation, cities became by far the largest emitters of CO₂. Urbanization has thus represented perhaps the most intricate and the most consequential interaction of grand transitions to modernity.

Pace of urbanization

Migration has been always driven by a combination of push and pull factors, with the desire for economic betterment and the escape from violence, persecution, famine, or environmental disasters as the leading factors in the first category and the promise of new beginnings, new opportunities, and often help from previously relocated relatives or friends in the other. During the 19th and the early part of the 20th century, a significant share of European migration to the Americas, Africa, and Australia went to rural regions (as large portions of the Canadian Prairies, American Great Plains, Argentinian pampas, and Australian outback were converted to new crop fields) and so did the intranational migrations in

China to the northeastern provinces ([Rasmussen 1975](#); [Lucassen and Lucassen 2014](#)).

In contrast, virtually all post-WWII intra- and international migration has been not just to urban areas but disproportionately to the largest cities. Between 1800 and 1900 London's population sextupled to 6.5 million ([Figure 2.5](#)), Paris expanded more than sevenfold to about 4 million, and New York's population grew nearly 60-fold to 3.4 million, and the process had created largely urban populations in several Western European countries before World War I. The share of the United Kingdom's urban population rose from one-third in 1800 to 78% in 1914, and the German share increased from 36% in 1850 to 60% in 1914, while at that time France was still more than half (56%) rural. For Europe as a whole the urban population increased from about 8% in 1800 (when it was only marginally higher than in the year 1000) to 28% in 1900 (UN 1969).



Figure 2.5 London Bridge in 1872. Large industrializing cities of the late 19th century had their major roads clogged by heavy traffic long before the arrival of motor vehicles. *The Illustrated London News*, January 1, 1872.

Immigration to the United States had two distinct destinations: while millions of late-19th-century immigrants came to large coastal and interior cities, millions settled on farms and in small towns on the Great Plains, and the urban population share rose from just 6% of the total in 1800 to 25% after the Civil War and to nearly 46% by 1914. More recently, Brazil's large-scale domestic migration has been marked by the same duality: large cities grew but millions have moved into rural areas, converting large areas of *cerrado* and deforesting parts of Amazonia in order to expand cattle pastures and cropping, including some of the world's most extensive soybean and sugar cane monocultures ([Keller et al. 2013](#)).

Modern urbanization had also shifted the centers of growth westward. During antiquity and the medieval era, most of the world's large cities were in East and South Asia, and the continent still had six out of ten of them by 1825, but by 1900 nine out of the ten of them were in Europe and the United States ([Jedwab and Vollrath 2014](#)). The rest of the world remained overwhelmingly rural, with less than 10% of people living in cities larger than 20,000 and no more than 5% in cities larger than 100,000. Progress during the first half of the 20th century was slow, but after World War II rapid urbanization became the norm throughout most of Asia and Latin America.

During the latter half of the 19th century, growing cities worldwide accommodated more than 50 million immigrants, with the largest individual intakes (in London, Paris, and New York) on the order of 2 to 4 million. These inflows were far surpassed a century later: between 1950 and 2000 urban population increased by 2.1 billion people, with more than 1 billion added through immigration. Another way to illustrate the accelerating urbanization is to compare consecutive time spans required to add a billion of city inhabitants. The first billion was reached in 1960: that is, after about 10,000 years of urban habitation; the second billion was added in 25 years (by 1985), the third one in 17 years (by 2002), and the fourth one in 15 years (by 2017).

In global terms, shares of urbanized population reached a third of the total by 1960 and surpassed 50% by 2008. In nearly all Western countries as well as in Japan and Latin America, the urbanization process is at or very near its saturation levels: in 2016 urban population shares were 82% in the United States, 86% in Brazil, and 94% in Japan, but only 76% in Germany ([World Bank 2019](#)). The Indian pace of urbanization has been slower, with

the rate rising from just 18% in 1960 to 33% by 2016. But migration keeps changing the population trajectories of some of the largest Western cities.

Decennial censuses show London's population growing from nearly 1.1 in 1801 to 8.6 million just before World War II and then declining to 6.8 million by 1981: the continuation of that trend would have reduced the capital to only about 2.1 million by 2050 ([Smil 2019a](#)). But the new wave of international immigration (part of the post-1980 globalization) lifted the total to 8.2 million by 2011. Similarly, New York, once the synonym for economic retreat, urban decay, and depopulation, has been revitalized by post-1990 immigration. By 2015 nearly 38% of the people living in the five boroughs were foreign born (the largest groups coming from the Dominican Republic, China, Mexico, and Jamaica) and they provided 45% of the city's labor force ([NYC Planning 2017](#)). Notably, the poverty rate of New York's immigrants has actually been a bit lower than for the native born, while the immigrants' homeownership was only marginally (about 3%) lower.

The most contentious recent immigration wave has been the one reaching the European Union from Africa and from the Middle East ([Okólski 2012](#); [Geddes and Scholten 2016](#)). In 2017 the largest number of asylum applicants were from Syria, Iraq, Afghanistan, Nigeria, Pakistan, Eritrea, and Albania ([Eurostat 2018a](#)). The recipients of the largest number of immigrants from non-EU countries have been Germany, the United Kingdom, Spain, and Italy ([Eurostat 2018b](#)). Most newcomers eventually find their way into major cities, and their influx presents a much greater assimilation challenge than in the United States, Canada, or Australia.

No country has been more changed by migration to cities than China, and the pace of change has been due in no small part to playing catch-up with the global trend. China's urbanization process was greatly restricted during the nearly three decades of Mao's rule. In 1949, the year of the Communist rise to power, China was only 9% urban, and when Mao died in 1976 the share had only doubled to 18% (UN 1969; NBS 2000). Subsequent economic modernization created the greatest urbanization surge in history with the largest sources of migration being from populous and poor interior provinces: Anhui, Sichuan, Hunan, Hubei, and Jiangxi were the leading five during the first decade of the 21st century ([Lu and Xia 2016](#)). China's urban population share rose from about 19% in 1980 to 36% by the century's end and to 57% by 2016. The urban total rose by 600 million people (from 190

to 790 million) with about three-quarters, or about 450 million people, due to migration.

By 2016 just over 80% of all Chinese urban residents were registered to live in their cities, but 220 million people (more than all the people in Brazil, the world's fifth most populous nation) living there were still registered in rural areas. These workers, often called the floating population, have built the new cities, they provide most of the labor for their manufacturing enterprises, and they run many urban services—and yet they have been treated as second-class citizens ([Zhao et al. 2018](#)). The reason has been the continuation of the household registration system (*hukou*) that was set up in 1958 and that ties families and individuals to their places of birth.

A peasant who moved from an interior province to get a manufacturing job in a coastal province becomes, after six months, officially a migrant but lives in the city without urban *hukou*. Numbers affected by these realities are very large: the floating population was less than 5 million people when the economic reforms began in 1980; a decade later it reached 21.6 million and in 2000 it was nearly 79 million, but by 2010 it soared to 221 million, or about 17% of China's population with about 60/40 shares of intra- and interprovincial moves, and the deltas of the Yangzi (including Shanghai) and the Pearl River (with Guangzhou and Shenzhen) are the two leading destinations of long-distance migration.

Among the 220 million migrants, there are nearly 40 million children, and up to 60 million children have been left behind by their parents in the care of grandparents and other relatives in distant villages ([Liang et al. 2016](#)). Reforms of the outdated registration system are needed to normalize the lives of migrants and the first steps were taken with a point-based *hukou* system in Beijing ([Xinhua 2018](#)). New rules will allow people who lived in the city for seven years to apply for permanent urban residence, and as the household registration system will be further liberalized the total number of registered urban residents may rise by 300 million by the year 2030 ([Liu and Liang 2017](#)).

Chinese and Indian urbanizations have led the eastward shift in the global total of large cities. In 1900 17 of the world's 25 largest cities were in Europe and the Americas and 6 in Asia; by the year 2000 Europe and the Americas had only 8 such cities and the Asian total rose to 16 ([UN 2016](#)). Ranking of city populations by size has been characterized by a high degree

of regularity conforming to an inverse power formula: the size of the population residing in the country's n th largest city is equal to $1/n$ of the largest city's total, corresponding to a power law with a coefficient of -1 (Zipf [1949]; Figure 2.6; Smil 2019a). The law is valid on the global level, and we do not need actual census data to demonstrate it: it is better to use satellite images which offer visible delineations of large settlements (Jiang et al. 2015).

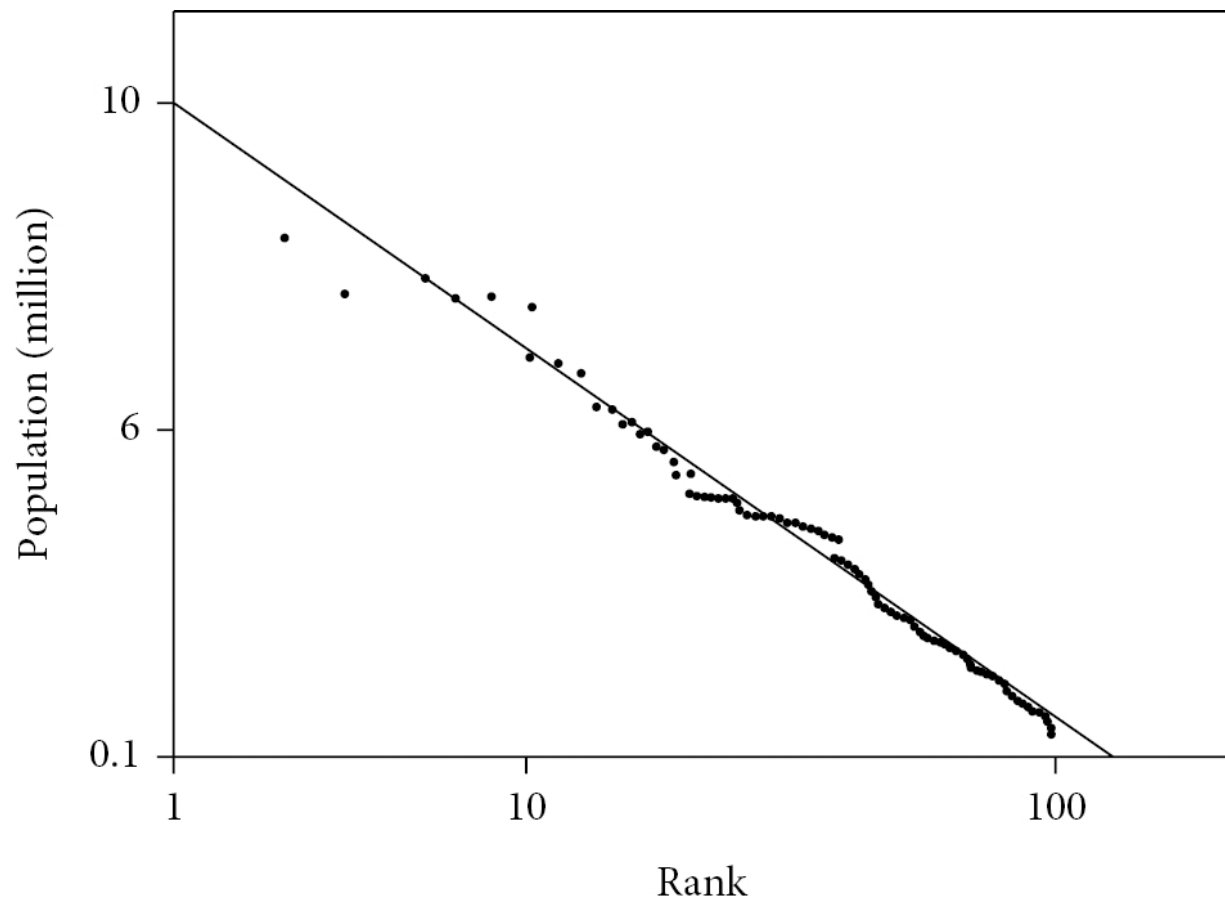


Figure 2.6 In his book *Human Behavior and the Principle of Least Effort*, George Kingsley Zipf extended his pioneering studies of word rank frequency to many other phenomena, including the ranking of the 100 largest US metropolitan areas. The inverse power relationship is close but not perfect.

Consequences of urbanization

City-driven transformations of social horizons and personal linkages have been profound. For at least 200,000 years our species lived in small, necessarily kindred, groups of foragers who rarely came into contact with

more than 100 people. For nearly 10,000 years herders lived in small, mobile groups and most peasants lived as extended families in settlements whose sizes were on the order of tens to hundreds of people, while a small fraction (well below a tenth until the early 19th century) inhabited towns with mostly hundreds to thousands of people.

Urbanization has been the key mechanism for dismantling extended families and creating gradually smaller family units. Fertilities in urban areas were significantly lower than in the countryside, but with the general decline of fertility rates, the gap has become relatively small even in some low-income countries (2 vs. 2.5 in Bangladesh). As increasing shares of women have joined the labor force many, even most, personal interactions have been transferred from family members to outsiders, be they caretakers or other infants in day-long child care or coworkers of parents or friends and acquaintances. These realities have created unprecedented combinations of reduced and expanded personal interactions, and of greater isolation coexisting with unavoidable mass participation. Similarly, urbanization-induced mobility expansion has led to shifts spanning orders of magnitude.

Worlds once circumscribed by walking distances around a village and later expanded to rare visits to nearby or distant towns and capitals began to include daily commutes of up to tens of kilometers and, for many urbanites, frequent intercity travel. The inconvenience of long commutes is much easier to accept than the threat of violence, especially when it assumes the form of intensive drug trafficking, gang warfare, and sexual assaults of women. None of these crimes is directly associated with city size: Tokyo, the world's largest city, is remarkably safe, and New York, written off as irreparably violent during the 1980s, has shown how crime rates can decline even in a multicultural megacity that has accommodated millions of immigrants ([Zimring 2013](#)).

The economic importance of cities is obvious. Large-scale urbanization drove modern industrialization and, in a deviation-amplifying loop, was driven by it. The period between 1860 and the beginning of World War I brought unprecedented cities-centered technical and scientific advances that introduced all fundamental innovations whose further development defined the 20th century: electricity generation, electric motors, steam turbines, internal combustion engines, production of inexpensive steel and aluminum, sound and image reproduction, wireless communication, and

industrial-scale synthetic chemistry. That level of innovation is why I have argued that the closing decades of the 19th century created the 20th century (Smil 2005). Subsequently, all of these advances have seen substantial performance and efficiency improvements that resulted in falling prices and mass adoptions, but the 19th-century inventors and innovators would readily recognize their creations in today's machines and processes because their fundamental operating principles have endured (Smil 2005 and 2006).

Growing cities have benefited disproportionately from increases in productivity; they have average per capita incomes higher than national means and they accumulate outsize shares of overall wealth. The economic dominance of cities is readily appreciated by looking at the results of a McKinsey study of the world's most populous 600 cities and at the forecast of their performance by the year 2025 (Dobbs et al. 2011). In 2010 600 of the world's largest cities housed 1.5 billion people, or 22% of the global population, but they generated more than half of the world economic product, with the top ten cities responsible for nearly 40% of the total. In 2007 380 cities in high-income countries accounted for half of the global economic product and 20% of it came from just 190 North American cities.

Continuing urbanization is adding almost 70 million new city residents a year, an equivalent of nearly two Tokyos, four New Yorks, or six Rios. By 2025 megacities will house about 2 billion people (25% of the global total) and account for 60% of the world economic product. Intrnational comparisons tell the same story of disproportionate economic importance: Tokyos, with 30% of Japan's population, generates nearly 40% of the country's GDP, and analogical shares for Shanghai are less than 2% and about 20%. The average per capita economic product in Beijing is about 2.2 times the national mean, and the median household income in San Francisco is about twice the national mean.

All of these disproportionate shares and totals reflect the advantages of agglomeration (Marshall 1890). Higher population densities reduce transportation costs, facilitate customer-supplier interactions and labor pooling, provide the best environment for aggregation and exchange of expertise, spur both cooperation and competition, and intensify economies of scale (Krugman 1991; Glaeser 2010; Behrens et al. 2014; Duranton and Kerr 2015). Benefits of agglomeration or, more accurately, coagglomeration, of enterprises are best illustrated by such iconic concentrations of businesses as New York, London, and Zurich (financial

services), Silicon Valley (hardware and software design), Hollywood and Bollywood (entertainment), and, the newest addition, Shenzhen (assembling consumer electronics).

These agglomeration benefits surpass locational advantages that used to favor cities with excellent ports or those controlling major transportation links. And [Gabaix \(1999\)](#) argued that most external shocks affecting urban growth decline as a city enlarges because it acquires greater economic resilience, and benefits from better education and policing as well as from higher taxes. The agglomeration trend has continued despite the diffusion of mass-scale long-distance transportation and, even more remarkably, despite the universal availability of instant communication and information sharing. Perhaps most remarkably, cities have kept on growing despite their often hard-to-tolerate environmental problems and other disadvantages: eliminating these downsides of urban experience might be impossible but urban dynamism has also contributed to their control and management.

Miseries of the 19th-century European and American urbanization can be best appreciated by turning both to dismal statistics and to contemporaneous investigative reports and fictional writing: all of them portray crowding and inferior living conditions, homelessness, crime, extraordinarily long working hours, child labor, ubiquity of infectious diseases, inadequate nutrition, and unchecked air and water pollution. Data from British surveys, parliamentary reports, and political pamphlets are as disturbing as are the novelistic portrayals of the extent and the depth of urban miseries fictionalized by Charles Dickens, Émile Zola, Thomas Hardy, and Elizabeth Gaskell ([Howden-Chapman and Kawachi 2006](#)). But even those dismal realities represented a change for the better for many immigrants.

Perhaps the most fundamental were substantial gains in the average quality of nutrition that resulted in rising consumption of traditional staples (bread, potatoes) as well as of meat, lard, butter, cheeses, cooking oil, and sugar. The nutritional composition of those more energy-dense diets might not have been optimal but they provided more affordable options for poor families. To criticize them would be an ahistorical mistake, as the more important achievement mattered: the late-19th-century industrial cities in Europe and North America provided, for the first time in history, a definite barrier against the famines. Results were easy to see almost instantly in lower rates of stunting and in rising average heights of children.

Other notable improvements began to transform public health (inoculation, piped-in treated drinking water, flushing toilets, sewers) and were soon reflected in rising life expectancies. Increasing numbers of urban children began to benefit from ready access and better quality of basic education, and rising incomes allowed even average-income families to spend more on better furnishing and clothing. Growing cities also supported many new libraries, organizations and institutions devoted to charitable works, participatory art performances (theaters, choirs), and physical fitness: those were the decades when participation in amateur activities (theaters, sports, outings to suburbs) became quite common.

Important steps were also taken to improve the environmental quality of urban living. These changes started with the introduction of smokeless lighting (using coal gas, first in 1812) and were eventually (starting in 1882) followed by the installation of public and indoor electric lights. The most radical steps involved large-scale demolition and reordering of old quarters, with Georges Eugène Haussmann's bold transformation of central Paris being the most influential example, which was followed in other European cities, including Brussels, Vienna, Madrid, and Prague ([Haussmann 1893](#); [Camiller 2002](#)). Public transportation became both faster and more affordable with the introduction of electric streetcars, subways, and suburban trains. More comprehensive urban planning approaches began to emerge, including Ebenezer Howard's influential concept of English garden cities ([Meacham 1999](#)).

Benefits of cities continue to be shared much less equitably than they should be in societies whose main concern would be a modicum of a decent quality of life for all (especially for children) rather than the unending quest for individual riches. Excessive urban inequalities have much in common with high crime rates: they are not direct functions of city size but rather reflections of many historical, economic, social, and cultural realities. Disparities in Tokyo are obvious but not revolting; Hong Kong, despite its strong social net, has a high level of inequality; and Africa and Latin America have cities with immense gaps between poverty and affluence. Johannesburg has an exceptionally high Gini coefficient in excess of 0.75; other capitals of inequality include Ethiopia's Addis Ababa (Gini at about 0.6), Colombia's Bogotá, Kenya's Nairobi, Mexico City, Peru's Quito, and Ghana's Accra ([Hugo 2015](#)).

And despite profound quality-of-life gains during the 20th century, all cities larger than one million impose many negatives on all of their inhabitants. Expensive housing is a common problem (in some cities with large immigration, prices are truly exorbitant), as are long (and often crowded) commutes and heavy street and highway traffic. The extent and intensity of other problems vary. As already noted, Tokyo has a low crime rate and an excellent subway system but the quality of its housing is inferior to the American norm. Beijing is extraordinarily polluted, and the entire city has been sinking because of its overuse of ground water drawn from deep aquifers. And no large city has come up with a satisfactory solution for the growing challenge of solid waste disposal. All of these problems reach their most intractable impacts in megacities.

Megacities

These exceptionally large agglomerations are defined as cities with more than 10 million people, but their actual areas and population totals vary widely, depending on which criteria are used. New York City ranges from 8.5 million in five boroughs to about 20 million in the New York Metropolitan Statistical Area to nearly 25 million in the Combined Statistical Area. Tokyo's 23 wards housed 9.25 million people in 2016, while Tokyo prefecture had 13.5 million people, the commuting area defined by the municipal government had nearly 39 million, and the National Capital Region had almost 44 million people in 2015.

In 1950 the world had only two megacities, New York and Tokyo, and while only Mexico City was added by 1975, the list grew to 18 cities by the year 2000. By 2016 the UN's global listing had 31 megacities, with 18 of them in Asia ([UN 2016](#)). Tokyo continues to lead and its nearly 39 million people would make it the world's 36th largest country among the UN's 200 states, slightly ahead of Canada. In the global ranking, the city is followed by New Delhi, Shanghai, Mumbai, São Paulo, Beijing, and Mexico City. As with all large cities, there has been a strong eastward shift in their global distribution: New York, the largest Western city, is now only in tenth place; Moscow, the largest European city, ranks 22nd; and by 2050 there will be no Western city among the top 20, as urbanization will be an overwhelmingly Asian phenomenon with an increasing share of megacities in sub-Saharan Africa, the region whose population will increase faster than

anywhere else. The potential for substantial additions to this list is best indicated by the fact that in 2016 the world also had 45 cities with populations between five and ten million people.

All megacities—be they such old metropolitan areas as London or Tokyo or such new agglomerations as Karachi or Lagos—share all the usual urban challenges but on more daunting scales. This scale also means that megacities face megarisks when the cities are subject to such natural hazards as earthquakes, hurricanes (typhoons), floods, tsunamis, and volcanic eruption or to terrorist attacks, and that insurers would face unprecedented payouts in the aftermath of such catastrophes ([Allianz 2015](#)). A leading reinsurance company concluded that many megacities are “virtually predestined to suffer major natural disasters” ([Munich Re 2004](#)). In addition, there are emerging concerns about protracted heat waves and about fires in skyscrapers.

Moreover, natural catastrophes that would severely affect or temporarily disable those megacities that have critical roles in the integrated global economy would have worldwide consequences for economic growth, as would the necessity of cutting off some megacities from mass-scale air travel in order to minimize the risks of spreading a new potentially pandemic infection. But such concerns do not seem to matter: megacities continue to grow even in countries with below-replacement fertilities. Consequently, in the not too distant future there will be the world’s first megacity of more than 50 million people, larger than Spain and about as large as South Korea.

Remarkably, some urbanization enthusiasts applaud this trend, claiming that as cities get bigger they get healthier and greener and make their inhabitants richer, smarter, and happier ([Batty 2013](#); [Glaeser 2011](#)). Such claims might refer to the evidence of some desirable shifts (larger and richer cities are forced to improve mass transport or face a near-permanent gridlock) but they are fundamentally misleading, ignoring the fact that large cities are the world’s most complex and most intensive dissipative structure, requiring enormous food, material, and energy inputs now sourced globally ([Bristow and Kennedy 2015](#)). Moreover, urbanization always leads to higher per capita consumption of food, water, raw materials, and energy, including energies that were used to build, and continue to be used to maintain, extensive urban infrastructures.

Moving from a traditional village to a modern megacity is commonly associated with the doubling or tripling of per capita claims on the biosphere's resources. The most important reason for much higher per capita energy use is the increased demand for electricity, from a single low-power light per room and perhaps a small TV in a village to residential high-rises where not only multiple lights but a refrigerator, cooking elements, a larger TV, and window air conditioning unit(s) are found in most apartments—and where a single standard toilet flush may consume more water than the daily household use for drinking and cooking in a traditional village (Smil 2014). As a result, India's per capita urban electricity use is nearly double the rural rate (Woodbridge et al. 2016), as is average tap water use in Chinese cities (Yu et al. 2015).

Megacities also create extreme urban sprawl and strong heat islands. By fragmenting habitats and destroying natural plant cover (particularly in coastal areas, above all in mangrove regions of the subtropics and tropics), sprawling cities reduce biodiversity, destroy farmland, and affect regional water runoff, thanks to the dominance of impermeable surfaces and the channeling of streams into concrete troughs. Heat rejection—from the unceasing operation of many energy converters and the high power density created by office and residential high-rises, industries, and traffic corridors—is potentiated by impervious surfaces and by restricted air circulation. This combination produces heat islands with temperatures a few degrees and up to 8°C higher than the surrounding countryside.

And, of course, megacities are also the most extreme examples of large-scale crowding. There is nothing new about very crowded urban living, as many premodern towns and cities had extreme population densities, but in megacities such conditions reach unprecedented rates. Densities (all in people/km²) go above 20,000 in Paris, 30,000 in Mumbai, and 40,000 in Manila, with the most densely inhabited quarters surpassing 50,000: such densities correspond to live human biomass of more than 2 kg/m², higher than for any other mammal and, incredibly, up to three orders of magnitude higher than the peak biomass of large ungulates grazing during the rainy season on East Africa's grasslands (Smil 2013a).

3

Agricultures and Diets

“First things first” is an adage that certainly does not apply to agriculture’s place in the modern world. Brief repeated fasting may be beneficial, but healthy living requires sustained, adequate food consumption and not just in terms of overall energy intake: normal growth and vigorous life need a balanced supply of macronutrients (carbohydrates, proteins, and lipids) and sufficient provision of micronutrients (vitamins and minerals). Although modern affluent societies are preoccupied with the consequences arising from a surfeit of food (ubiquitous dieting, obesity) or from consuming specific foodstuffs and nutrients (worries about fats, sugar, vitamins), food production has not been a major public concern.

This conclusion is not based on some casual impressions. Google’s Ngram viewer, quantifying the appearance of specific words in printed sources in seven major languages since 1500, shows the following relative maximum frequencies for the four subjects of this inquiry into grand transitions: population and energy have been the most frequently encountered words (peaking at 0.02%), environment and economy (0.01%) came up only half as many times—and agriculture trails with the peak of just 0.004%, while nutrition ranks even lower at 0.001%. Peak times of those word frequencies are also revealing: frequency for environment is peaking right now; concerns about energy peaked in the 1980s, about population in the 1970s, and about agriculture in the 1950s.

Economists offer yet another, outright irrational, perspective as they ask, Why should we be concerned about agriculture? After all, the sector is economically marginal, as it contributes only a tiny share of total GDP in modern societies. Indeed, in 2016 US farm production accounted for 0.7% of the country’s GDP (BEA 2018)—but the economists’ argument is as illogical as it is infuriating. My suggestion: just let them live off the output (whatever it might be) of the most important sector, which now accounts for more than 20% of GDP, the category labeled by the Bureau of Economic

Analysis as “finance, insurance, real estate, rental, and leasing.” *Bon appétit!*

Society’s collective lack of concern about food production is a perfect testimony to the enormous achievements that have resulted from more than a century of agricultural transitions whose accomplishments belong to a large category of productivity improvements. Combinations of plant breeding (improved cultivars, genetically modified crops) along with agronomic, technical, and managerial advances (ranging from the introduction of crop rotations to the use of field machinery, synthetic nitrogenous fertilizers, and other agrochemicals) have increased the productivity of land (rising crop yields), inputs, and labor ([Bindraban and Rabbinge 2012](#)).

Typical yields of staple crops are now multiples of traditional harvests, some (including American grain corn) even an order of magnitude higher. A combination of improved efficiencies of irrigation and fertilizer use, lower pre-harvest losses (thanks to the application of herbicides and pesticides), and almost complete mechanization of field tasks has resulted in impressive labor productivity gains and in unprecedented food abundance ([Federico 2008](#); [Olmstead and Rhode 2008](#)). The average time spent in producing American wheat illustrates the productivity trend ([Smil 2017a](#)). In 1800 a New England farmer worked with two oxen, a wooden plow, and brush harrows to prepare a field; broadcast seed by hand; cut the crop by sickle; and used flails to thresh it. These tasks took more than seven minutes of his labor to produce a kilogram of wheat that, after milling, would make two small loaves of whole wheat bread.

In 1900 a Great Plains farmer deployed a team of heavy horses to pull a steel gang plow, iron-tooth harrows, and a seed drill to put the crop in, and one of the first horse-drawn combines to harvest it and thresh it. These advances cut the time for producing a kilogram of wheat to about 25 seconds, 95% reduction in time, compared to 1800, or an 18-fold increase in labor productivity. By the year 2000 large tractors (some with power equivalent to 500 strong horses), wide-swath implements, and high-capacity combines reduced the human labor required to produce a kilogram of wheat to less than six seconds, more than quadrupling the typical labor productivity during the 20th century. Remarkably, during the second half of the 20th century the average growth of US agricultural productivity surpassed that of manufacturing productivity ([Dimitri et al. 2005](#)).

Economies of scale have resulted in a smaller number of larger and more specialized farms: between 1900 and 2000 the number of US farms was cut by two-thirds and their average area had nearly tripled (to about 175 ha), and while in 1900 a typical farm produced five different commodities, by the year 2000 the mean was barely above one ([Dimitri et al. 2005](#)). Yet another way to illustrate this concentration and specialization is by comparing the shares of US farms with domestic animals: in 1900 90% of all farms had chicken, and close to 80% had cattle, milk cows, and hogs; a century later about half of the farms had cattle, but fewer than 10% had other animals (USCO 1902; USDA 2018).

Productivity gains made most of the agricultural labor force redundant and allowed its mass migration to industrializing cities. Rising productivities meant that even as the agricultural labor force kept on declining—in the United States from 74% in 1800 to 40% in 1900 and to just 1.7% by the year 2000 ([Lebergott 1966](#); FRED 2018)—and even as populations were increasing, per capita availability of plant foods has been rising. No less importantly, modern cultivars and modern agronomic methods had gradually reduced yield fluctuations and, supported by growing international trade, had eliminated any risk of protracted food shortages and outright famines.

I will first review the fundamental shifts that comprise the epochal transitions in field agriculture. Rising inputs of anthropogenic energies have been the common denominator of these developments as crop breeding, agronomic advances, mechanization, fertilization, irrigation, and innovations in animal husbandry would have been impossible without substantially subsidizing natural photosynthetic conversion and animal metabolism by fossil fuels and primary electricity. As Howard Odum put it, the idea that more food comes from higher efficiencies in using solar energy “is a sad hoax, for industrial man no longer eats potatoes made from solar energy, now he eats potatoes partly made of oil” ([Odum 1971](#), 116). Production of animal foods has also benefited from breeding as well as from better feed quality and from optimized feed regimens. Disease prevention made it possible to realize economies of scale in massive concentrated animal feeding operations.

The next focus will be on shifts in food supply at the retail level and on notable nutritional transitions. Much like the demographic transition, the dietary transition has followed trajectories characterized by universal shifts

(most notably decreased consumption of staple grains and legumes and increased intakes of lipids and animal protein), as well as by national peculiarities. For example, unlike that in all other affluent countries, Japan's dietary transition has not resulted in a much higher consumption of sugar, and Turkey's dietary transition has not led to high per capita meat consumption.

In closing I will review the key consequences of these shifts and summarize their influences on other grand transitions. New concerns have arisen with regard to nutrition's role in higher rates of cardiovascular mortality, diabetes, and obesity. Much expanded affordability and variety of food have been due not only to rising productivity but also to a massive and now truly global trade in food and animal feed, and have led to unprecedented internationalization and hybridization of tastes as well as to unwelcome environmental impacts.

Productivity Transitions: Crops and Animals

The most decisive development in modern food production has been its transformation from an endeavor powered solely by photosynthetic conversion of solar radiation to a hybrid activity that has become critically dependent on rising inputs of fossil fuels and electricity (Odum [1971](#) and [1983](#); [Fluck 1992](#); Ramírez 2005; [Smil 2008b](#)). In traditional farming, photosynthesis of annual and perennial crops produced all food and all animal feed that, in turn, sustained human labor and animal draft used in field work and in manufacturing of farm implements and building of homes and of shelters for domestic animals. Recycling of plant matter and of animal and human wastes replenished soil fertility, and laborious manual weeding or hoeing controlled competing plant growth.

Wooden tools dominated, and a limited variety of iron implements used in farming (sickles, scythes, plow shares) were made from the metal smelted in charcoal-fueled furnaces. Ruminants lived off pastures and off harvested hay; penned animals were fed food processings, kitchen wastes, and (rarely) small amounts of grain; and many animals (pigs, poultry) were left to forage. As for the aquatic foodstuffs, capture of wild marine and freshwater invertebrates and fish was in some regions complemented by

traditional aquaculture practices whose productivity was improved in parts of Asia by fertilizing ponds with organic matter.

Non-solar energy inputs

Solar radiation will always remain the largest and an absolutely indispensable energy input driving crop photosynthesis, but production of new phytomass could not have reached such high rates if it were not for the multitude of anthropogenic energy inputs that are derived mostly from fossil fuels and also from primary electricity. These inputs amount to direct and indirect external energy subsidies that support and enhance the natural photosynthetic process. Direct subsidies include all fuels and electricity used to operate field and processing machinery. Field machinery, trucks, and irrigation consume mostly liquid fuels, while electricity is indispensable for crop processing (milling, extraction) and in animal husbandry (chopping and grinding feed, mechanized milking, air conditioning).

Indirect subsidies (embodied or embedded energies) comprise mostly many fossil energy inputs used to produce agricultural machinery, implements, and chemicals. Principal inputs are coke for iron smelting and electricity to make steel and aluminum, and hydrocarbons for the synthesis of ammonia (the starting point for producing nitrogenous fertilizers), pesticides, herbicides, and plastics. Fuels and electricity are also needed to extract and to formulate other fertilizers (phosphate, potassium compounds), to repair machinery and to dry, process, and store crops after harvest. In comparison to these major flows, energies required to develop new crops, new animal breeds, and new agronomic, animal husbandry and aquacultural practices (supporting basic and applied research, field work, and extension activities) constitute relatively minor—but now absolutely indispensable—anthropogenic subsidies.

Common energy use in modern cropping is between 8 and 15 GJ/ha for dryland cereals and legumes but up to 40 GJ/ha for irrigated, high-yielding corn, measurements that mean that the equivalents in terms of energy per harvested crop mass are mostly between 1.5 and 4 GJ/t ([Piringer and Steinberg 2006](#); [Smil 2008b](#); [Sørensen et al. 2014](#); [Achten and Van Acker 2015](#); [Degerli et al. 2015](#)). Corn, America's largest crop, requires 15–20 GJ/ha and with good yields (around 10–11 t/ha) this need prorates to 1.4–2

GJ/t; irrigation using water drawn from deep aquifers can double typical rates; no-till cropping and regular rotation with nitrogen-fixing alfalfa can cut them almost in half ([Sørensen et al. 2014](#)). Intensively grown vegetables require much higher energy inputs: tomato cultivation in heated glasshouses in Germany or the United Kingdom can be 100 GJ/t or more ([Neira et al. 2018](#)).

A comparison helps for visualizing the ubiquity and the magnitude of energy subsidies in modern farming. Direct and embodied energy inputs to the cultivation of American wheat range between 3.1 and 4.9 GJ/t, with 3.9 GJ/t (rounded to 4 MJ/kg) as the mean ([Piringer and Steinberg 2006](#)). In order to produce about 700 g of flour needed to bake a loaf of whole wheat bread, a Kansas farmer had to invest about 2.8 MJ of fuels and electricity. If we assume that all of this input energy was diesel fuel (a simplification done to facilitate a mass comparison), that investment would be equal (with energy density of diesel at about 37 MJ/L) to nearly 80 mL, or a third of a cup used to measure liquid food volumes in American kitchens. Eating just one home-baked loaf a week would require more than 4 L of diesel fuel a year to grow the wheat—and eating store-bought white bread (including the energy cost of milling, baking, and distribution) would easily double that need.

Several studies have traced agricultural energy transitions on national or regional scales ([Gingrich et al. 2018](#)). Depending on the agroecosystem, external energy subsidies have risen by one to two orders of magnitude since the middle of the 19th century, from rates lower than 1 GJ/ha to 10–100 GJ/ha during the closing decades of the 20th century. Nonrenewable energy inputs in northern France grew from near zero in 1860 to almost 13 GJ/ha in 2010 ([Kim et al. 2018](#)), in Quebec they had multiplied about 60-fold between 1871 and 2011 ([Parcerisas and Dupras 2018](#)), and in Spain they rose about 20-fold between 1900 and 2008 ([Guzmán et al. 2018](#)).

Energy cost of modern meat production is always dominated by the cost of animal feed. To produce a single breast of 170 g a broiler chicken had to consume about 600 g of feed, or roughly 8.7 MJ, and in volume terms that would be equivalent almost exactly to a cup of diesel fuel. The total energy cost of meat must be enlarged by 10–30% in order to account for direct uses of electricity and liquid and gaseous fuels to heat, air-condition, and clean the structures housing the animals. Additional energies are required to move traded food and feed. This, now truly global, trade ranges from mass

shipments of soybeans and corn from the Americas that are used to feed Asian pigs and poultry to exports of fresh and frozen seafood and high-value-added foods (cheeses, chocolate) and beverages.

Bulk shipments are used for seeds, container shipments for processed foodstuffs that require cooling or refrigeration. Shipping costs are substantial even if we leave out all indirect energy inputs required to build vessels and port facilities. For example, soybean cultivation in Brazil's Center West and South, the two leading farming regions, are, respectively, 4.8 and 3.9 GJ/t—but transportation costs could be the same or even higher: trucking from the interior to the coast requires 3 GJ/t, and shipping to Rotterdam consumes 1.5 GJ/t ([da Silva et al. 2010](#)).

Quantifying total energy used by global food production can be done in only a highly approximate manner. During the 20th century the global population increased 3.7-fold and the total area of harvested cropland expanded by only about 40%—but my reconstruction of energy inputs into modern farming indicates that anthropogenic energy subsidies (excluding energy used in global food and feed trade) increased 90-fold, from just 0.1 to about 12 EJ ([Smil 2017a](#)). By 2015 the total, including transportation costs, was about 15 EJ—and we still do not have to add the cost of seafood whose capture is heavily dependent on diesel fuel used by the global fishing fleet.

Specific accounts show differences of three orders of magnitude, from as little as 10 L/t to capture small, abundant pelagic species (anchovies, mackerels, sardines) to as much 10,000 L/t to catch some crustaceans (shrimps and lobsters), and the worldwide mean is about 700 L/t ([Parker and Tyedmers 2015](#)). In energy terms the mean rate equals about 26 GJ/t, and two skewers of shrimp (ten medium-sized crustaceans weighing the total of 100 g) could have required one liter (about 4.2 US cups) of diesel fuel! Global aquacultural output has been closing on capture fisheries (80 vs. 91 Mt in 2016) and it requires direct energy inputs to operate pens, ponds, or tanks (maintaining enclosures, feeding, aerating and recirculating water), and indirect inputs to supply feed ([Hornborg and Ziegler 2014](#)).

Feed production for carnivorous fishes requires catching wild species (anchovy, capelin, herring, mackerel, pilchard, krill) to produce protein-rich fish meals and fish oil ([Cashion 2015](#)). Surveys of energy use in modern aquaculture indicate energy costs from 11 GJ/t for carp grown in ponds to nearly 100 GJ/t for sea bass in cages, the range similar to energy intensities

of capture fisheries ([Muir 2015](#)). Production of dietary seafood protein requires only around 100 GJ/t for long-line mussels to more than 1 TJ/t for caged sea bass. Using data from [Muir \(2015\)](#), simplified volume comparison shows that a small 150-g aquacultured sea-bass fillet would cost about 22 MJ of energy to produce, an equivalent of nearly 2.5 cups of diesel fuel.

Even when assuming a relatively low mean energy subsidy cost of 25 GJ/t for all seafood, the 2015 output of 200 Mt would have required about 5 EJ, raising the grand total of nonrenewable energy inputs to food production to about 20 EJ/year. For comparison, in the year 2015 the global use of all primary commercial energies was about 485 EJ; thus food production claimed only about 4% of the total. Direct energy use by US agriculture was about 850 PJ in 2012, or about 0.8% of the total ([Hicks 2014](#)). These low shares are excellent examples of disproportionately large effects of relatively small inputs that are often encountered in the behavior of complex systems.

A classic nutritional example is another illustration of this disproportionate effect. Europe's 18th-century sail ships that roamed the oceans on their voyages of discovery could be laden with abundant supplies of food (plenty of hardtack and preserved meat), but as long as they did not carry relatively small amounts of antiscorbutics (lemon or lime, or at least some sauerkraut) their crews suffered and died of scurvy ([Lind 1753](#); [Lamb 2016](#)). Sailors could have a surfeit of carbohydrates and protein (or, alternatively, do well with their temporary small deficits), but missing at least 20 mg of vitamin C per day could end their journeys and their lives.

Similarly, modern civilization could continue to prosper even after reducing its transportation (or industrial, residential, or commercial) energy use by the amount far surpassing the total of energy subsidies used to produce its food—but without that 4% of global energy devoted to the modern food production it would be impossible to feed the world's current population of more than 7.5 billion people. How did this dependence on anthropogenic energy inputs come about? The first important innovation did not involve any fossil energies; it was an intensification of a well-appreciated traditional practice of widespread adoption of regular crop rotations that included nitrogen-fixing leguminous crops (vetches, clovers, and alfalfa).

Such rotations have been known since antiquity but the common use of optimized sequences (such as Norfolk's four-year rotation of wheat, turnips, barley, and clover) dates only to the middle of the 18th century. Subsequent widespread adoption of the practice had at least tripled nitrogen available to non-leguminous crops and began to raise long-stagnant staple grain yields ([Campbell and Overton 1993](#)). [Chorley \(1981, 92\)](#) concluded that this "generalization of leguminous crops and the consequent increase in the nitrogen supply . . . was of comparable significance to steam power in the economic development of Europe in the period of industrialization" and that it justifies the label of Agricultural Revolution.

But this intensification of solar agriculture would not suffice to support growing populations—and hence a concurrent development saw the first applications of nitrogen fertilizers other than recycled organic wastes (manures and crop residues) and plowed-in green manures (leguminous cover crops). Guano was the first (still organic) nitrogenous fertilizer that contained much more nitrogen than recycled wastes. US imports of these accumulated droppings of tropical seabirds preserved on some dry islands began in 1824. Peruvian guano remained the world's most important commercial nitrogen fertilizer until 1870, when it was surpassed by shipments of Chilean nitrate, the world's first inorganic source of nitrogen containing 16% of the element ([Smil 2001](#)). Exports began in 1830, surpassed 1 Mt/year by 1895, and peaked at nearly 3 Mt/year during the 1920s.

The second wave included better ways of field preparation and new ways of grain harvesting proceeding from a simple reaper to the first combines. The best medieval heavy plows were wooden with a wrought-iron share ([Andersen et al. 2016](#)), the first cast-iron plows appeared just before the end of the 18th century, and John Deere introduced his wrought-iron moldboard plow in 1843, but steel plows became common only during the 1860s once Bessemer's process had made the metal affordable ([Magee 2005](#); [Smil 2017a](#)). The opening of America's Great Plains and Canada's prairies for large-scale cropping would not have been possible without steel riding plows and, later, without large gang plows whose six to ten shares could cut heavy sod and required up to 12 horses to pull.

Until the 1830s, when the first mechanical reapers became available in the United States, traditional grain harvesting was done by sickles and scythes ([Casson 2017](#)). The first harvester came in the late 1850s, the first

fully mechanized grain harvester, able to discharge bound sheaves, two decades later. Combines drawn by horses were introduced in California in the 1880s. There were also important advances in dairy operations, including the deployment of the automatic cream separator ([Lampe and Sharp 2018](#)). The next three concurrent advances were the Haber-Bosch synthesis of ammonia, gradual elimination of animal draft in field work and transportation, and diffusion of better cultivars.

Agrochemicals and machinery

During the last decade of the 19th century it became clear that the combination of population growth, urbanization, and demand for better nutrition would require harvests that would be impossible without increasing inputs of nitrogen. Adequate amounts of this plant macronutrient could not be secured even by the most assiduous recycling of organic wastes whose nitrogen content is usually well below 1% ([Mikkelsen and Hartz 2008](#)). Higher inputs of nitrogen in traditional farming required extraordinarily high applications of organic manures, with annual rates often reaching 10 t/ha ([Smil 2001](#)). Collecting, moving, and spreading these wastes was the most demanding task in traditional intensive farming.

In 1909 Fritz Haber of the Karlsruhe University was the first chemist to demonstrate the synthesis of ammonia under high pressure in the presence of iron catalyst ([Smil 2001](#)). This invention was rapidly commercialized under Carl Bosch's leadership (hence the Haber-Bosch process) by BASF, at that time the world's leading chemical company, with the first ammonia deliveries in 1913 ([Figure 3.1](#)). During World War I ammonia was diverted to production of explosives and the growth of the fertilizer industry in Germany, in several European countries, and in the United States began only during the 1920s. Further interruptions due to the economic crisis and World War II postponed the expansion of mass-scale production of nitrogenous fertilizers until after 1950.

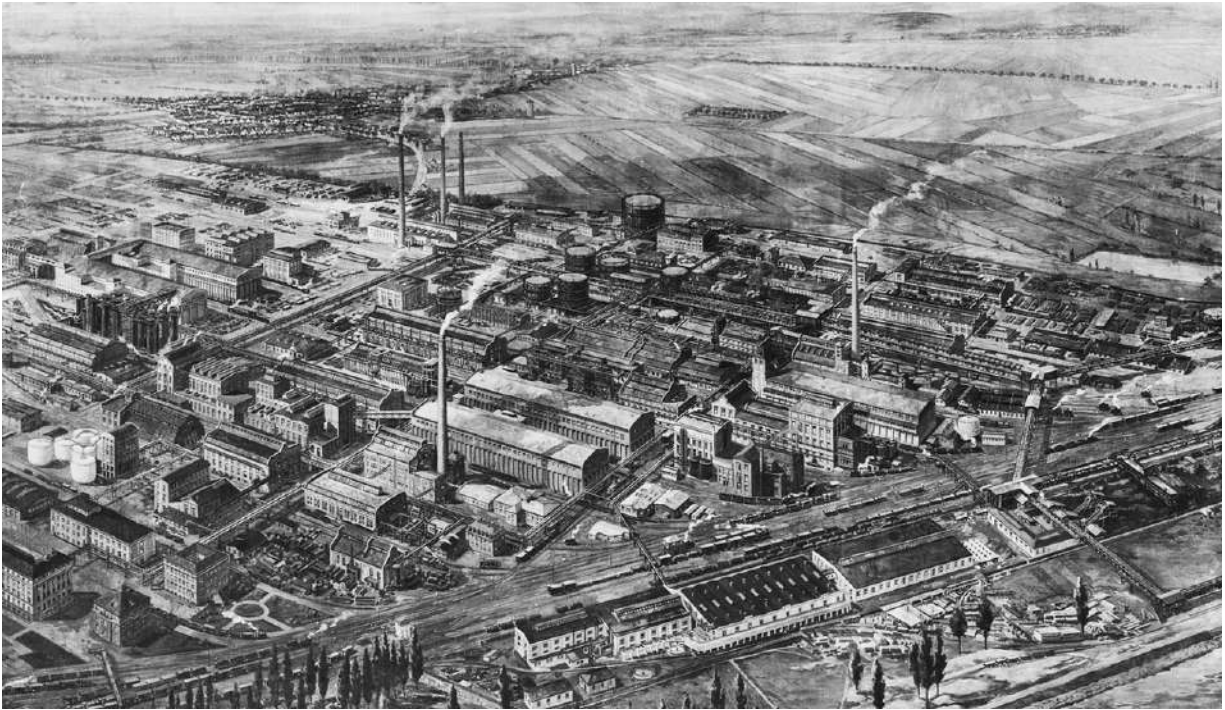


Figure 3.1 Construction of BASF's ammonium plant in Oppau, Germany, begun in May 1912 and the first product shipment was ready less than 16 month later. This painting by Otto Bollhagen is from 1920.

Ammonia used to be converted mostly to nitrates (ammonia nitrate is 34% N) or sulfates (ammonia sulfate is 21% N), but (with 46% N) urea is now the dominant solid fertilizer. Worldwide synthesis of NH_3 rose from only about 4 Mt N in 1950 to 30 Mt by 1970, to 85 Mt by the year 2000, and to 150 Mt N by 2017, with some 80% of the total output uses as fertilizer (USGS 2018). Europe, the United States, and the USSR led the production until the 1970s before China then became the world's largest producer, now accounting for 30% of the global total. I have argued that the Haber-Bosch synthesis was perhaps the most consequential (defined as having made the greatest difference for the largest number of people) technical invention ever because without it (given the prevailing diets) it would have been impossible (even if all other inputs were available) to produce food for about 45% of today's global population (Smil 2011).

But nitrogen alone could not drive the modern transition in crop productivity. We have known since 1840 when Justus von Liebig published his work on limiting nutrients that the three key macronutrients must be supplied in appropriate ratios in order to maximize photosynthetic output

([Liebig 1840](#)). Production of phosphorus and potassium fertilizers is much less energy intensive than synthesizing ammonia. Early ammonia production, based on hydrogenation of coal, required well over 50 GJ/t of NH_3 , while the latest large ammonia plants (using natural gas as both the feedstock, to derive hydrogen, and the fuel) need less than 30 GJ/t of NH_3 ([Smil 2014](#)). Nitrogen applications vary widely; for US corn they are at least 100 kg N/ha, an equivalent of 3–5 GJ/ha. Phosphorus is supplied mostly by superphosphates produced by mining of phosphate rocks and their treatment with acid at the cost of 18–33 GJ/t. Potassium comes mostly as potash, a mineral whose excavation and crushing takes less than 2 GJ/t. China, Morocco, and the United States are the largest producers of phosphates, and Canada, Russia, and China of potash.

Higher fertilization-driven yields present greater feeding opportunities for pests, and nutrients added to soils can be also tapped by prolific weeds. Those uses are why the introduction of insecticides, fungicides, and herbicides has been such an important part of the modern agronomic package. Their first applications took place in the United States in the mid-1940s; syntheses of their active ingredients have relatively high specific energy needs (mostly between 100 and 200 MJ/kg) and the final cost (after formulating, packaging, and distributing) is as much as 300 MJ/kg ([Unger 1996](#)). But because these agrochemicals are applied at low rates (typically 1–2 kg/ha) their relative energy cost (around 1 GJ/ha) is low.

Replacement of draft animals (mostly oxen, horses, and water buffaloes) was an epochal shift from the reliance on animate prime movers to vastly more powerful inanimate energy converters and it eliminated considerable strain on crop production. Before World War I, growing feed (oats, corn, and hay) for American horses and mules required nearly a quarter of the country's cultivated land, preempting the planting of food crops or feed crops for meat and dairy animals ([Smil 1994](#)). By 1910 the United States had only about a thousand small tractors; by 1918, when the number of draft animals peaked at nearly 27 million, their count rose to 85,000. Improvements during the interwar years (power takeoff to be used by various implements, massive rubber tires, efficient diesel engines) presaged the post-1950 expansion, and by 1960 the US Department of Agriculture stopped counting draft animals.

In 1900 a strong horse could develop sustained power equal to the exertion of six or seven men; the early gasoline tractors delivered an

equivalent of 15–20 strong horses, after 1950 machines rated at more than 100 horsepower became common, and the most powerful North American tractors now rate about 600 horsepower and are able to pull implements 12 m wide. Similarly, the most powerful corn harvester can now cut the swath of 12 m or 32 rows of the crop. In Europe's poorer regions horse-drawn farming continued for a few more decades after it ceased in the United States and millions of drafts animals are still working in Asian and African fields.

Specific energy requirements of field operations (plowing, harrowing, cultivating, spraying, harvesting) vary with crops, climates, and soils but except for plowing (600–1,200 MJ/ha) they are mostly between 150 and 500 MJ/ha, adding up to grand totals of 1.5–2.5 GJ/ha ([Smil 2008b](#)). Diesel engines and electric motors also made it possible to provide adequate irrigation, with watered areas increasing from about 50 million ha in 1900 to about 330 million ha in 2015 ([FAO 2019](#)). Energy embodied in agricultural machinery (for producing steel and other materials and for final assembly) is considerable. But because of long service periods (at least a decade) their prorated energy cost (per unit of area or unit of harvest) is lower than the cost of fertilizers, while energy cost of irrigation can rival those of fertilizer production or can ever surpass them when water is drawn from deep aquifers.

Massive reduction of labor force has been the most consequential economic impact of agricultural mechanization. As already noted, this reduction has allowed the tripling of average American farm size during the 20th century, and the largest farms in Brazil now cover hundreds of thousands of hectares. Cultivation of vegetables, fruits, and nuts remains more labor intensive but their harvesting is getting mechanized. Remarkable new machines include an automated strawberry harvester using a camera-based vision system to check each fruit for its form and color before activating precise cutting blades when it finds a ripe berry ([Pepperl + Fuchs 2018](#)). Similarly, unlike the old mechanical grape harvesters (that knocked off berries and mixed grapes, leaves, and stems with the fruit), lasers and positioning sensors of the latest harvesters can identify and selectively de-stem and sort material other than grapes ([Pellenc 2019](#)). Mechanization has also changed animal husbandry: automatic feed supply, stall cleaning, manure removal, and hygienic milking of cows are now common.

Better crop varieties

Development of better staple grain cultivars began with hybrid corn in 1908. Traditional open-pollinated varieties yielded just between 1.3 and 1.8 t/ha. New double-crossed varieties were introduced during the late 1920s, by 1939 they accounted for 90% of US corn, and by 1960 they raised the average US yield to 3.4 t/ha ([Hoegemeyer 2014](#)). New single-crossed cultivars more than doubled that yield to 8.6 t/ha by the year 2000. The first genetically modified insect-tolerant corn was released in 1996 by Monsanto, and the first genetically modified glyphosate-tolerant transgenic corn was introduced in 1998 by Dekalb Genetics and was adopted rapidly, claiming 89% of all plantings by 2016 and boosting average yield to 10.6 t/ha in 2015 ([Crow 1998](#); [USDA 2017](#)).

Increased wheat yields were achieved by redistributing the photosynthate within the plant. Traditional varieties were tall (easily lodging) and because their harvest index (the ratio of crop yield and the total above-ground phytomass) was as low as 0.2 and no higher than 0.3 they produced three to five times as much straw as grain ([Donald and Hamblin 1976 Figure 3.2](#)). As a result, typical wheat yields were only around 1 t/ha in dry regions with little or no fertilization and around 2 t/ha on better soils in rainy areas. The first modern short-stalked cross, Norin 10, was released in Japan in 1935 and it provided the foundation for post-WWII wheat breeding in the United States and at the CIMMYT, International Maize and Wheat Improvement Center in Mexico ([Lumpkin 2015](#)).



Figure 3.2 Engraving by Pieter van der Heyden (after Peter Bruegel the Elder) of *Summer (Aestas*, 1568) illustrates the man-size height of traditional wheat cultivars: that is, their low grain/straw ratio. In contrast, modern short-stalked cultivars are just knee high. Metropolitan Museum of Art, Harris Brisbane Dick Fund, 1926.

Two semi-dwarf CIMMYT crosses released in 1962 had launched what became known as the Green Revolution. Their harvest index was 0.5 (yielding as much grain as straw) and average global yield is now above 3 t/ha, China is above 5 t/ha, and the highest national means are above 7 t/ha (FAO 2019). Short-stalked varieties have also revolutionized global rice harvest. A harvest index of IR 8, the first high-yielding cultivar released by the International Rice Research Institute in 1966, was as high as 0.6 (Smil 1987), and while the best traditional varieties yielded no more than 2–3 t/ha, the Japanese mean is now above 5 t/ha and the Chinese mean is close to 7 t/ha.

Obviously, even the best varieties can produce only a limited number of grains per plant and hence an essential step to improve the yield has been to increase average seeding rates. By 2015 US corn plantings averaged 78,000 seeds/ha, and the highest rates were nearly 90,000 seeds/ha, compared to just 55,000 in 1985 and to traditional (open-pollinated crop) densities of 37,000–45,000 seeds/ha ([Pioneer 2017](#)). Supporting nutritional and water demand of such densely planted crops can be done only by assuring optimal fertilization and supplementary irrigation. Not surprisingly, since 1970 nitrogen used in US corn growing has nearly doubled and although only about 20% of cornfields are irrigated, their water use per hectare far surpasses the demand by any other crop ([USDA 2013](#)). Higher yields reduced land needed per unit of output and allowed reforestation of previously farmed land, a trend particularly notable in parts of Europe and in Eastern North America ([Ausubel et al. 2013](#)), as well as the shift of crop production from food to animal feed.

Animal feeding

In traditional agricultures draft horses and mules were the only animals that were given concentrate feeds because their power was indispensable for field operations. As already noted, at their maximum count these animals consumed feed harvested from a quarter of America's cultivated farmland. In contrast, use of draft animals was most restricted in densely populated regions of East Asia where limited amount of farmland had to be devoted to food crops. Ruminant animals relied on pastures and hay, production of beef and mutton was very limited, and omnivorous pigs consumed crop and household waste and were often herded to forage in forests. Poultry remained mostly free running and was given a bit of grain.

Scientifically based feeding standards developed during the course of the 19th century, the first mixed feeds came during the 1870s, and easily handled and highly digestible pelleted feed was introduced by American companies (Purina, Cargill) only during the 1920s ([Coffey et al. 2016](#)). Pellets were eventually enriched with synthetic vitamins and antibiotics. After World War II American meat and egg production began to shift to a new mode of feeding that has eventually resulted in the near-disappearance of mixed farming and in the dominance of large-scale centralized animal-feeding operations (CAFOs) that operate separately from crop production

(hence landless feeding operations). Europe followed soon afterwards and China joined the trend only during the 1990s.

Differences in average numbers of animals kept on traditional American mixed farms in 1900 and by modern operations in the year 2000 was about 50-fold. In 1900 farms reporting specific domestic animals averaged 3.5 horses (and in the South 2.2 mules), 12 heads of cattle, and 13 pigs (USCO 1902). A century later there were no horses and mules, but 75% of all cattle operations had more than 100 heads and nearly 40% had more than 500 animals, while average hog farms housed 600 animals (USDA 2000). In turn, average modern operations are dwarfed by the largest CAFOs, including beef feedlots with tens of thousands of animals (a maximum of about 150,000); with big hog operations with more than 1,000 sows, piglets and pigs; and with more than 10,000 broilers or turkeys under a single roof ([Smil 2013b](#); [Imhoff 2004](#)). CAFOs depend on an affordable supply of mixed feeds that contain optimized shares of nutrients; in many countries they have been increasingly produced from imported plant and animal ingredients.

Sources of carbohydrates have shifted from traditional oats and wheat to higher-yielding corn, and soybeans are the main sources of protein. Until after World War II the cultivation of this ancient legume was confined to East Asia, but then the United States became the world's largest producer and exporter, followed by Brazil, Argentina, and China ([Prodöhl 2009](#)). Other major sources of feed protein include oilseed meals, dehydrated alfalfa, processed waste animal tissues, and fish meals ([Sapkota et al. 2007](#)). Global mass of compound feeds increased from 290 Mt in 1975 to 591 Mt in the year 2000 and to more than one billion metric tons (1.017 Gt) in 2016, with China, the United States, the European Union, and Brazil accounting for nearly 60% of the total (IFIF 2017). In 1980 China had only a rudimentary feed industry producing 1 Mt of compound feed a year, but in 2016 its total was the world's highest at 187 Mt.

Animal feeding led to five major transitions. Cropping, traditionally dominated by production of plant foods, has shifted to animal-feed cultivation that now accounts for even more than half of total production; there have been large increases in total counts of animals kept for meat, eggs, and milk; typical feeding times to slaughter have been much reduced; average slaughter weights have increased; and major declines in production costs resulted in rising per capita consumption of meat.

Traditional farmers in populous Asian countries produced almost no feed crops, while in Europe and North America they grew feed almost solely for bovine and equine draft animals. This proportion is still true in India, where nearly 90% of all major crops end up as food and only 6% as feed; China's shares are 58% and 33%, and food crops are now only about half (55%) of the global harvest with feed making up 36% ([Cassidy et al. 2013](#)). In the United States feeds have dominated for decades: before the adoption of mass-scale ethanol fermentation from corn about two-thirds of all US domestic crop consumption (and three-quarters of corn harvest) were destined for feed, while recently nearly 40% have been diverted to ethanol (USDA 2018; [Schnepf 2011](#)).

The best reconstruction puts the global total of all large domesticated mammals at about 1.5 billion heads in 1900 ([HYDE 2018](#)). A century later horse numbers were halved, cattle count had tripled, water buffalo total had nearly quadrupled, sheep count had nearly quintupled, and the aggregate numbers of large mammals approached 4.3 billion heads ([FAO 2019](#)). This growth, combined with continued tropical deforestation and slaughter of wild megafauna (above all elephants and rhinos) for tusks, horns, and skins, has resulted in a profound redistribution of aggregate masses of animals. In 1800 the zoomass of wild mammals was larger than that of domesticated species. By 1900 my estimates indicate that the zoomass of cattle alone was twice that of wild mammals; by the year 2000 the ratio became lopsided, with the domesticated zoomass more than 20 times larger than that of wild mammals, and with cattle having mass some 250 times higher than all surviving elephants ([Smil 2013a](#)). These dismal trends continued during the first two decades of the 21st century, with African elephants facing extinction over large areas of the continent (WWF 2018a) and with cattle numbers still rising.

Substantial reduction of feeding spans is best illustrated by comparing typical requirements for pigs and chicken ([Smil 2013b](#)). Traditional pigs were slaughtered only after 12–15 months when they weighed 49–60 kg; now they go from CAFOs to the market just six months after weaning, when they average 90 kg. Traditional free-roaming chickens were killed after three to four months when they weighed about one kilogram—while the US broilers now average 2.5 kg after just six weeks of feeding.

All of these trends are self-limiting and some growth trajectories have already ended as new plateaus or even gradual declines have set in. In all

affluent countries the stock of cattle and pigs have been either stagnating or declining: French cattle from 24 million heads in 1975 to 19.3 million in 2016, US cattle from 132 million to 92 million heads, Polish pigs from 21 to fewer than 11 million heads during the same period ([FAO 2019](#)). The average slaughter weight of cattle and pigs leaves little room for further gains, and the average weight of broilers is already excessive, as oversized breasts shift the bird's center of gravity forward, restricts its movement, and strains its legs and heart ([Turner et al. 2005](#); AWI 2010). Further substantial reductions of feeding spans are unlikely, and per capita consumption of red meat, particularly beef, has seen some pronounced declines in nearly all affluent countries.

The best long-term documentation of feeding efficiencies is available thanks to input/output ratios calculated by the USDA ([Smil 2000a](#); USDA 2018; [Figure 3.3](#)). These ratios are expressed in terms of corn feeding units (converting all feedstuffs to a standard equivalent containing 15.3 MJ of gross energy per kg) that are required to produce a unit of live weight. Cattle's large body mass, long gestation and lactation periods, and a higher basal metabolic rate than expected for animals of their mass preclude any major efficiency gains—and the USDA series has shown no obvious long-term trend since the early 20th century, with rates for cattle and calves around 13 and cattle on feed between 9 and 10 kg per kg of live weight (USDA 2018).

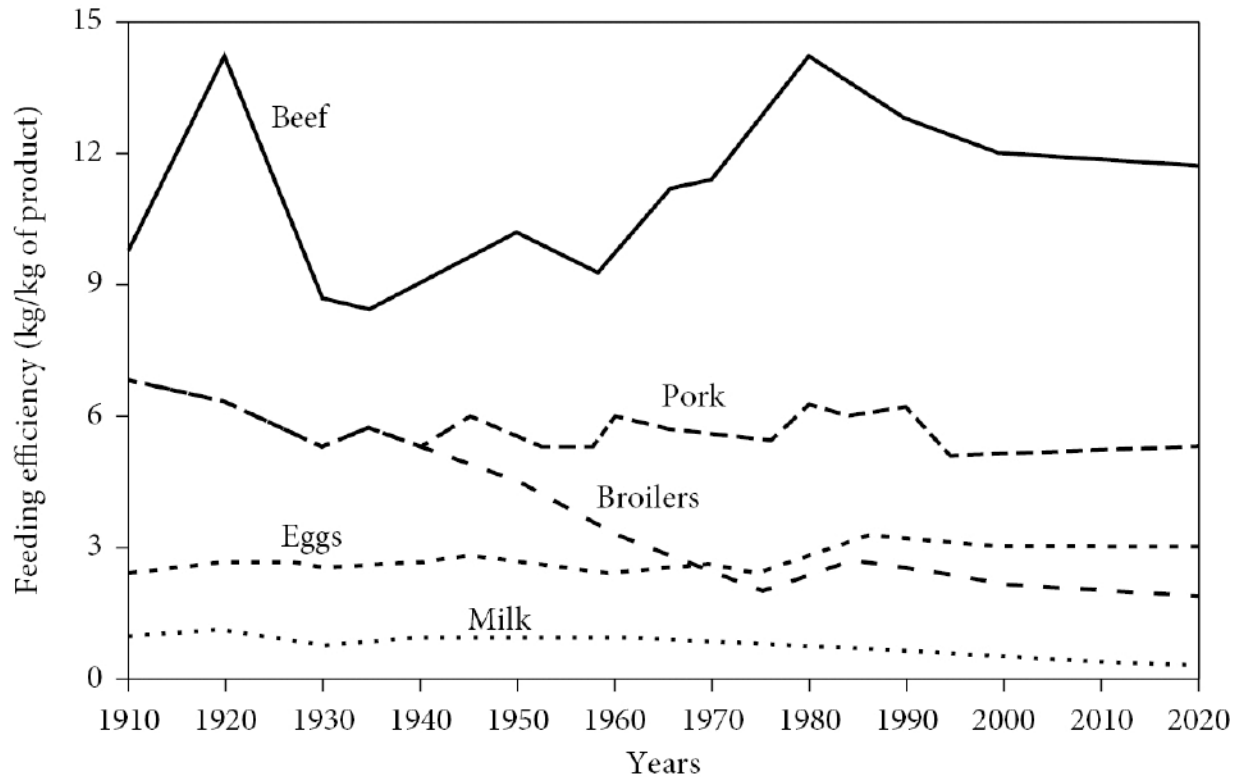


Figure 3.3 USDA animal feeding ratios, 1909–2019. Beef, inevitably, is always the least efficient meat to produce pork is more than twice as efficient but without any long-term gains; broilers, the most efficient meat producers, now do better than egg-laying hens.

Because of their inherently low metabolic rates (about 40% lower than might be expected for their body mass), pigs have the lowest relative feed requirements among domesticated mammals but modern breeding has actually negated some of gains arising from optimized feeding. Conversion of feed to fat is about 60% more efficient than conversion of feed to lean meat, and as consumers demand leaner cuts, modern, less fatty breeds require more feed. Two decades of slight decline (from 6.7 units of feed per unit of live weight in 1910) were followed by stagnating performance for the rest of the 20th century (with rates fluctuating between 6.4 and 5.9 during the 1990s) but new records were reached recently, with the nationwide rate ranging mostly between 4.9 and 5.1 feed per kg of live weight in 2015 (USDA 2018).

Fast growth rates, short life spans, and the rearing in confinement (limiting their energy expenditure) have brought impressive efficiency gains to broiler production. This USDA feeding efficiency series started only in the early 1930s, when more than 5 units of feed were needed per unit of live

weight; by the mid-1960s the rate declined to less than 3 and since 2008 it has been between just 1.6 and 1.8 kg/kg of live weight, a gain that explains the increasing affordability and rising consumption of this white meat. In contrast, long-term efficiencies of egg and milk production have improved only marginally, and there have been no gains in producing mutton and lamb meat. As expected, data for aquacultured species show relatively low feed conversion ratios, mostly between 1 and 2 units of feed per unit of live weight ([Fry et al. 2018](#)).

A more accurate appreciation of energy costs of meat production is to adjust the rates for edible portions. Producing chicken meat needs about 3 units of feed for every unit of edible weight, while the multiples are 9-fold for pork and at least 25-fold for beef ([Smil 2013b](#)). Similar adjustments for aquacultured species show average around 3, and the range from about 1.8 for the Atlantic salmon to more than 4 for tilapia and giant prawns ([Fry et al. 2018](#)), findings that mean that most of aquacultured seafood is not less feed intensive than chicken.

Food Supply and Dietary Transitions

Diets have to reflect the dominant modes of food provision, and in preagricultural societies these modes had ranged from hunting and harvesting marine species to foraging in arid environments. The first mode of subsistence offered a relatively easy access to highly nutritious aquatic animals and hence to exceptionally high intakes of animal protein and fat: these were the best-fed prehistoric societies. In contrast, diets of foragers in arid environments were based on collecting tubers and seeds and supplementing them with scavenged and hunted meat of ungulates. Consequently, there was no typical foraging diet but it is safe to conclude that (maritime hunters and gatherers aside), plant foods provided 65–70% of all food energy, protein intakes were usually adequate, about 20% of all food energy was derived from lipids, intakes of micronutrients (vitamins and minerals) were generally above the currently recommended daily rates, and access to food within small foraging groups was highly egalitarian ([Cummings et al. 2014](#)).

In contrast, the richest (ruling and urban) minorities in settled societies had a privileged access to a wider variety and better quality of foods. Here

is just one of many possible egregious examples that were recorded by chroniclers. In his posthumous Renaissance cookbook, Cristoforo Messisbugo, who served as a steward of Casa d'Este in Ferrara, lists courses for 14 different banquets, some with 140 different dishes, others that included over 30 kinds of fish, some comprising 17 rounds of service with eight dishes apiece and concluded by cheese and fresh, glazed, and marinated fruits ([Messisbugo 1549](#)).

As for the quotidian peasant diets, there is no evidence of any clear secular improvement of the food supply during the millennia of premodern farming. Average food intakes were marked by fluctuations, stagnations, and recurrent shortfalls: there were feasts and famines. We know that even in the best-off European countries typical diets remained marginal until the late 18th and the early 19th century. Surveys conducted by Frederick Morton Eden throughout England during the closing decade of the 18th century found mostly starchy monotonous diets barely adequate to provide nutrition for people who were expected to work hard in workshops or in fields.

Here is a description what “labouring classes” ate in a parish just north of Sheffield:

Oat-bread is very generally used . . . they eat water-pottage twice, and sometimes three times, a day: it is made with boiling water, oatmeal, and onions; to which sometimes a little butter is added: the proportions of oatmeal and butter have been much lessened since the rise in the price of those articles took place ([Eden 1797](#), 814).

For those who never baked their own bread or studied the art of baking: any bread containing mostly oats, barley, or rye (as the breads of poor people often did) will be a heavy lump, as those cereals lack wheat's gluten that makes leavened breads possible ([Myhrvold and Migoya 2017](#)).

In Asia similarly marginal subsistence diets were the norm for most of the 20th century. That was the case even in Japan of the early 1900s, decades after the country began its modernization drive (following the Meiji restoration in 1868) and after it defeated China in its first aggressive war (in 1895). Milled rice was scarce and animal protein was almost completely absent. Here is how a man born in 1904 in the area just some 60 km northeast of the capital and 40 km west of the Pacific shore (around lake Kasumigaura in the Ibaraki prefecture) recalled the prevailing diet:

In our village a meal of a mixture of rice and barley, with six parts barley to four parts rice, would've been considered above average. . . . Fresh river fish we almost never had up in the mountain where I lived. . . . We never saw any fresh sea fish, either, from one year to the next. But at New Year most families bought one salted salmon, though only after an awful fuss ([Saga 1987](#), 187).

The shifts created by dietary transitions are best illustrated by contrasting average annual per capita supply of major foodstuffs. New population-wide patterns became clearly discernible in Europe and North America during the 19th century, the process continued during the 20th century, and after World War II it proceeded rapidly in East Asian countries as well as in parts of Latin America. By the century's end all of these regions had either already completed their dietary transition or had distanced themselves from traditional eating patterns ([Caballero and Popkin 2002](#); [Smil 2004](#); [Weng and Caballero 2007](#)).

There has been an unmistakable shift toward the Western (European/North American/Australian) pattern of eating but this change does not mean that the diet rich in meat and lipids acts as a universal beacon and that all modernizing countries will move as close to it as their purchasing power increases. [Seckler and Rock \(1995\)](#) posited two distinct patterns of food consumption as the two alternative attractors during the process of dietary transition. The first one, the Western pattern, raises the daily mean of per capita food supply to more than 3,200 kcal and more than 30% of all available food energy comes from animal foodstuffs.

The second one, the Asian-Mediterranean pattern, has average daily supply rates below 3,200 kcal/capita and animal foodstuffs supply no more than 20–25% of all food energy. Japan is by far the best example of a major country where a rapid dietary transition shifted the overall pattern clearly in the direction of the first attractor—but well before reaching its typical rates it settled into a new, moderate level of eating. Average daily per capita food supply in Japan is now about 2,700 kcal; average daily intake is just 1,900 kcal; annual meat consumption is only about 33 kg/capita; and seafood contributes 25 kg/capita ([SB 2017](#)). Given the country's aging population, it is most likely that the average diet will become even more frugal.

This is an apposite place to stress that all of the widely available data on average per capita food supply should not be, as they commonly are, mistaken for actual consumption rates. Supply rates are calculated from available data on annual crop and animal production adjusted for net stocks and trade as well as for such processing losses as milling rates for grains

and extraction rates for oil, while meat supply is usually reported as carcass weight. Food balance sheets of affluent nations are highly reliable but for many low-income countries they are based on the best production estimates reconstructed at the FAO's Rome headquarters ([FAO 2019](#)). In any case, supply averages derived from food balance sheets are always considerably higher than actual food intakes. Food balance sheets do not account for losses that take place between harvests and slaughters and food availability at the retail level. In addition, there are post-retail losses due to household storage and table waste.

Consumption rates can be found only by properly designed and carefully executed nutritional surveys conducted by dieticians visiting the selected families and measuring and recording actual food intakes. These are expensive undertakings and hence they were never widely adopted, and even Japan's National Health and Nutrition Survey, which relied on them for decades, abandoned the practice ([Ikeda et al. 2015](#)). Data on dietary intake thus come universally from unverified verbal and textual reports and are just "mere guesstimates of whatever the respondents are willing and able to remember and report about what they think they ate and drunk in the past, or want the investigators to think they consumed" ([Archer et al. 2018](#)).

Differences between per capita food supply and consumption reveal the extent of food waste. Food in traditional societies was wasted because of the lack of protection against many insects and rodents, and viral and fungal diseases caused serious pre-harvest losses, while the combination of poor storage, absence of refrigeration, and expensive or nonexistent transportation (precluding sales of seasonally abundant but perishable foodstuffs to more distant markets) resulted in substantial post-harvest losses. Advances in crop management and food storage have reduced such losses but have not made much difference to food waste at retail and household level. Frequent eating out has become another major contributor to increased food waste.

Staple grains

In mass terms, the foremost dietary change has been the pronounced decline in average per capita consumption of traditional staples, grains, and tubers (the principal source of food energy and dietary protein) as well as of complementary leguminous grains (assuring an adequate supply of essential

amino acids from plant-based diets). Dominant staples differed among the regions (wheat in Europe and North America, rice in Asia, peas and beans in Europe, soybeans in East Asia) but downward trends have been similar. In traditional diets staple carbohydrates supplied often as much 80% and rarely less than two-thirds of all food energy, while in modern societies their shares fell to less than a third, or even to less than a quarter ([Smil 2000a](#)).

In those societies in which consumption of the preferred staple cereal was supplemented, and often equaled or even surpassed, by eating coarser varieties, the latter grains had retreated faster as higher incomes made it possible to buy more of traditionally favored highly milled wheat (white flour being 85% of the entire grain) and rice (white rice being less than 70% of the entire grain). Removal of bran, endosperm, and germ milling also removes dietary fiber, vitamin Bs, and some minerals (Fe, Mg, Zn), yielding flours that are less healthy than whole-grain cereals ([Mozaffarian et al. 2013](#); [Wu et al. 2015](#)). But this reversal of value is of very recent origin: traditionally, highly milled grains always signified a higher consumption status. In Europe this shift led to declines in eating barley, oats, and rye; in East Asia it resulted in lower consumption of barley, buckwheat, and millets.

According to the Japanese historical statistics, in consumption surveys rice provided 50% of all food energy in 1870, 53% in 1880, and 52% in 1886, and barley covered an additional 27–28% ([Bassino 2006](#)). Shares of the main staple often rise temporarily with higher income before retreating: in 1950 rice supplied about 59% of Japan's food energy; a decade later it was 47% but subsequent diversification of diets halved it to 23% by the year 2000 and recently it has been around 22% ([Ricepedia 2018](#)). This use translates to eating more than 350 g of rice (uncooked weight) per capita a day during the late 1950s, less than 200 g/day three decades later, just above 160 g/day by the century's end, and only about 120 g/day by 2015, only about a third of the peak value reached two generations ago.

Remarkably, in mass terms Japanese now consume annually less rice than dairy products (milk, yogurt, ice cream, and cheeses) that were completely absent in the country before the defeat and American occupation in 1945 ([Smil and Kobayashi 2011](#)). While average rice per capita consumption is now below 45 kg/year, domestically produced and imported dairy products add up to more than 70 kg/year in terms of milk

equivalent. Of course, in food energy terms rice is still ahead, as the energy density of milled grain is more than five times that of milk. Similarly, average American per capita wheat flour supply (mainly to bake bread) was nearly halved between 1910 and 1970, from about 97 kg to 50 kg (USBC 1975). This decline was followed by a partial recovery to about 66 kg during the late 1990s. That temporary rise was caused by the expansion of fast-food eateries and resulting increases in consumption of wheat for pizzas and buns for hamburgers, sandwiches, and hot dogs.

Substantial decline in the consumption of leguminous grains has been a universal phenomenon with only a few notable exceptions. In traditional and largely vegetarian societies annual intakes of legumes were as high as 25 kg (in India) and above 10 kg/capita in Latin America, providing commonly 15–25% of all dietary protein. Consumption of beans and peas was never that high in premodern Western Europe, greater affordability of meat had further reduced it already before World War II, and recent food balance sheets show annual supply averages just between 1–1.5 kg/capita, with legumes providing less than 1% of all food energy and 2% of dietary protein (FAO 2019).

Average US annual legume supply is, at just over 4 kg/capita, much higher than in Europe, thanks both to the presence of large immigrant populations from Latin America and to the mainstream adoption of Mexican-style bean-rich dishes by some of the country's fast food chains. And even India's *dal* has become a weaker pillar of the country's vegetarian cuisine, with per capita supply of legumes falling by half between 1960 and the year 2000 (to just 11 kg) and then recovering a bit to about 14 kg, putting the country behind Brazil's now record annual supply (nearly all of it being beans) of more than 16 kg, or about 25% less than half a century ago (FAO 2019).

Interestingly, the average annual Japanese per capita supply of soybeans—processed mainly into *shoyu* (soy sauce) and *tofu* (bean curd)—has changed little since the 1970s, remaining at between 7 and 8 kg/capita, while actual consumption of tofu (the coagulate is 85% water) had more than doubled from less than 7 kg/year in 1960 to about 16 kg by the late 1970s and then has declined to about 10 kg/year (Miura 2009). Three reasons explain the worldwide retreat of legumes. As meat becomes more affordable it offers to all but strict vegetarians a superior source of complete protein. Dry legumes are not cooked as easily as milled grains, and their

digestion is not as easy, due to the presence of oligosaccharides. Meat, dairy products, sweeteners, and dietary fats have more than made up for the retreat of staples.

Meat and milk

Meat, especially energy-dense fatty meat, was the most cherished foodstuff among foragers but actual consumption rates differed widely. While the Neolithic hunters of megaherbivores or more recent hunters of North American bison ate plenty of fresh and preserved meat, hunting in tropical rain forests (with small animals living in tree canopies) had low rewards and could support only limited meat eating. Very low to low consumption of meat in nearly all agricultural societies was not a reflection of voluntary abnegation—but of limited grazing land in densely populated regions and poor crop yields with harvests destined almost exclusively for food.

But in medieval and early modern Europe many varieties of meat and offal were always available and elites enjoyed meat during extravagant feasts. [Flandrin \(1989\)](#) lists the numbers of animals killed to honor the installation of George Neville as Archbishop of York in 1466: six wild bulls; 104 oxen and peacocks; 204 cranes; 304 hogs; 400 (each) swans, herons, and plovers; 1,000 sheep and egrets; 2,000 suckling pigs; and large numbers of chicken, geese, ducks, and pheasants for 2,500 invited guests.

Typical amounts of meat eaten by peasants and urban laborers remained low even during the early decades of industrialization. The already cited Eden's report shows that between 1787 and 1796 poor rural laborers in England and Wales ate just 8.3 kg/year ([Clark et al. 1995](#)), and even three generations later meat consumption among low-income groups was just above 10 kg ([Fogel 2004](#)). In Japan proscription of meat eating lasted until the Meiji restoration (1868). Even after the Meiji emperor encouraged his subjects to eat meat (and introduced meat rations in the army) meat consumption rose from 800 g/capita in 1900 to just 2 kg/capita in 1939 ([Smil and Kobayashi 2011](#)).

And although meat was valued in traditional diets of China, Vietnam, and Korea, its consumption among peasants remained negligible until the second half of the 20th century. During the 1920s annual meat intakes in poor northern provinces averaged just a few kilograms per family, or a mere fraction of a kilogram per capita, as meat was eaten only two or three times

a year during high celebrations ([Buck 1930](#)). In Jiangsu, the province surrounding Shanghai, the rates were much higher at about 5 kg/capita, but the nationwide mean during the early 1930s was below 3 kg/capita ([Buck 1937](#)). Meat was thus a negligible source of protein.

Industrialization, rising domestic output and production, and (starting in the early 1880s) increasing imports of frozen meat from New Zealand, Australia, and North America lifted the British meat supply to almost 35 kg/capita in 1850 and to nearly 60 kg in 1900 ([Perren 1985](#)). Wartime drops aside, it had subsequently fluctuated around that level for half a century before it rose to more than 70 kg/year by 1970 and to nearly 80 kg by the year 2000 (all rates are in carcass weight). French meat supply had a similar trajectory: it had doubled during the 19th century to 40 kg/capita, and it reached 55 kg in 1950, 60 kg in 1960, and nearly 100 kg by the year 2000 ([Monceau et al. 2002](#); [Duchène et al. 2017](#)).

Denmark, now with five times as many pigs as people, became the global leader in breeding, food safety, and animal welfare: it now exports 90% of its pork production, as well as many live animals. The most impressive gains in the European meat supply took place in the Mediterranean region where low intakes (less than 20 kg/year in Greece, Spain, and Portugal) lasted until the 1950s. Subsequent increases accelerated once these countries had joined the European Union in the 1980s. The Spanish supply had more than quintupled between 1960 and 2000 and at 112 kg/capita it had surpassed the rates of such traditionally meat-eating countries as Germany, France, and the Netherlands.

Extensive grazing lands and plenty of animal feed made the United States the world's leading meat-eating nation already during the 18th century and this position only strengthened with the westward expansion during the latter half of the 19th century. What Wilbur Atwater, a pioneering American nutritionist, wrote in 1888 remains true today: Americans are “eating in excess of energy demands, with excesses of meats, especially of the fatty kinds” ([Atwater 1888](#), 259). There is now more lean pork and much more poultry, but 52% of all food energy in a Big Mac still comes from fat (McDonald's 2019). The US supply averaged about 75 kg of meat/capita (carcass weight) in 1910; the Great Depression brought a slight temporary dip, but even WWII rationing kept the rate at 59 kg/capita (Bentley 1998), while GI rations were 106 kg of red meat, 165 kg in the Navy. Postwar supply peaked in 1971 with about 90 kg of carcass weight and the cut of

30% by 2015 was more than made up by rising consumption of poultry, which reached half of the total meat supply of about 95 kg/capita.

Widespread dieting and various health concerns have resulted in uneven meat consumption in all affluent countries. Recent French data (actual consumption) illustrate this trend (Duchène et al. 2017). French meat eating has been declining for decades and by 2013 37% of adult French were *petits consommateurs*—those who ate meat only in small amounts and whose intakes averaged just 80 g/day (or about 29 kg/year)—compared to 28% of those who were heavy meat consumers, averaging 217 g/day, or 79 kg/year. The Japanese meat supply remained below 5 kg/capita during the 1960s, then it quadrupled to about 22 kg by 1980, and it peaked at nearly 30 kg by 2010 (Smil and Kobayashi 2011). Since that time, it has declined by more than 10% and further declines must be expected as the population ages. China's dietary transition has been even faster as the country has moved from a barely adequate diet dominated by staple grains and basic vegetables to an average per capita supply that has been above the Japanese mean since the mid-1990s, and contains relatively high shares of meat and fish.

China's *Statistical Yearbook* for 2018 shows nationwide meat production of 86.24 Mt (carcass weight) and that prorates to average annual output of 61.8 kg/capita, while the section on household consumption lists 38.5 kg/capita (29.5 kg/capita of red meat and 9 kg/capita of poultry, as edible, boneless meat) as the nationwide mean (NBSC 2019). Pork is China's dominant meat (it accounted for nearly 83% of the red meat consumption in 2018), poultry is in the second place, and both beef and mutton consumption are very low. Per capita consumption of about 38 kg of red meat and poultry in 2018 was more than triple the amount in 1975 (the last full year of Mao Zedong's life) and about 2.3 times higher than in 1995 (nationwide mean of 16.6 kg). The post-1995 doubling was accompanied by diminishing disparity between rural and urban consumption: in 1995 their ratio was 0.55; by 2018 it was about 0.8.

In many affluent countries per capita intakes have either reached saturation levels (Germany, the Netherlands) or they have significantly declined from their peaks reached mostly a generation ago (France, Spain, the United States). One fundamental switch has taken place in all regions with increasing post-WWII consumption: gradual decline in eating red meat (particularly beef) and rapid ascent of poultry consumption, above all broilers produced by mass-scale feeding. This shift (or what the French

called *la guerre aux matières grasses*) began once animal fats had been (not quite correctly) identified as a principal reason for high blood cholesterol and ensuing heart disease.

Brazil has been a notable exception among the middle-income countries: its already fairly high meat supply (mostly beef produced by grazing on *cerrado* grasslands as well as on land reclaimed from the Amazonian forest) has tripled since 1975 and it is now close to 100 kg/year. In contrast, the supply in Southeast and South Asia remains low, with both Indonesia and Pakistan below 15 kg/capita, and with India being the only populous nation that has not shown any shift toward more meaty diets, still averaging less than 4 kg/capita. Ethiopia has now passed that (about 7 kg) and Nigeria, Africa's most populous nation, averages less than 10 kg/capita.

Milk is one of the perfect foods, a source of complete protein, fat, sugar, calcium, and vitamin D. But milk was not a universally consumed food throughout the Old World, and milking animals were absent in the Americas and Australia. Lactose malabsorption (lactose intolerance or lactase deficiency) is impaired ability to digest milk's sugar (composed of glucose and galactose). This condition is rarely present among infants, but in most of the world's population intestinal lactase declines after infancy. As a result, milk drinking may cause just mild abdominal discomfort, but in many individuals it can induce nausea, cramping, and vomiting ([Suarez and Savaiano 1997](#)).

Evolutionary selection produced a complex lactase deficiency pattern. Pastoral societies (many African and Central Asian groups) and settled cultivators who kept milking animals (Europe, Indian subcontinent) have retained the ability to digest lactose in adulthood, while neighboring non-milking cultures (parts of Africa, most of East Asia) are largely lactose intolerant. But dietary transition has produced two surprising outcomes: direct consumption of milk has declined in countries that were traditionally its leading consumers, while the intakes of dairy products have been rising in countries that had no history of milking and whose populations were considered to be overwhelmingly lactose intolerant.

American per capita supply of fresh milk and cream was nearly 140 kg in 1909, it peaked at 171 kg in 1945, and then it declined to 97 kg in the year 2000 and to 79 kg in 2015, more than a 40% decrease in a century (USDA 2018). The total supply of milk (fresh and for making dairy products) declined at a slower rate. Similar patterns of stagnation or declines in

overall milk consumption can be seen in countries with the highest per capita supply (Netherlands at over 300 kg/year, France at nearly 250 kg/year). Milk's adoption in formerly non-milking cultures is explained by its convenience as a source of excellent nutrition and by the fact that lactase intolerance is not an absolute barrier for most of the affected population: most adults can regularly drink small volumes of milk. [Yoshida et al. \(1975\)](#) found the only about 19% of Japanese adults have lactase intolerance with intakes of up to 200 mL—and daily drinking of that volume would amount to 73 L/year, close to average rates in some European countries.

Moreover, consumption of fermented dairy products presents fewer or no problems: unripened cheeses (ricotta, cottage cheese) retain less than 30% of the original lactose, while ripened cheeses have only a trace of lactose. Yogurt contains most of lactose present in milk but it also supplies a variety of bacterial enzymes that aid in its digestion ([Suarez and Savaiano 1997](#)). No non-milking culture adopted dairy products faster and more widely than Japan. Consumption data start in 1906, when the annual per capita supply averaged less than a liter a day; it rose to 5.4 L/capita in 1941, prorating to less than 15 mL/day with consumption highly concentrated in largest cities: when the US forces occupied Japan in September 1945 only a tiny share of the country's population had ever tasted milk or cheese.

During the 1950s, annual milk supply rose to 25 L/capita and milk was regularly served by the National School Lunch Program, contributing to the elimination of previously obvious urban-rural discrepancy in childhood growth ([Takahashi 1984](#)). By the year 2000 the total milk supply averaged 82 L/capita, and by 2015 the mean declined to about 70 L/capita ([FAO 2019](#)). China, traditionally the world's largest non-milking society, has increased its per capita milk supply by an order of magnitude since the mid-1970s, from less than 3 L to 35 L by 2015, surpassing South Korea. Not surprisingly, India, with the world's largest ancient dairy culture, has been increasing its milk supply as the purchasing power of its population rises: recently it has been about 90 kg/year, more than double the rate of half a century previously.

Sweeteners, fats, and fruits

The first two food categories are generally seen as the least desirable components of modern diets, particularly because of their excessive

presence in fast food. In contrast, fruit has become the paragon of modern healthy eating. In both instances, realities are more complex. Even some of the formerly proscribed fats are now enjoying at least a partial rehabilitation, while a closer look reveals that modern fruit production and trade often exact an exceptionally high environmental price in order to supply micronutrients (fruit is devoid of protein, and, except for avocado, it also contains no lipids).

Refined sugar and high-fructose syrup have been making up large shares of total mass of deserts and snacks worldwide but especially in North America, with its surfeit of shakes and doughnuts as well as with ubiquitous and supposedly healthy nutrition bars. A Krispy Kream donut (40 g) is 25% sugar; Smoothie King's Hulk Strawberry contains 253 grams (quarter of a kilogram!) of sugar ([Smoothie King 2018](#)). In Europe sugar was treated first as a medicine; Muslim invasions brought regular cane cultivation to Sicily and al-Andalus. Throughout the Middle Ages, however, sugar remained largely an expensive import with growing consumption limited to the richest groups.

Refined Renaissance cooking used sugar as “an excellent accompaniment to everything . . . and human nature finds great pleasure and delight in its sweet flavor” ([Felici 1572](#), 136). Once the colonial powers had set up large sugar cane plantations in Brazil and in the Caribbean, imports began to rise, by the late-18th-century sugar consumption became more common in Western Europe, and the post-1811 diffusion of the process capable of refining sugar from beets began to provide the continent's own sugar supply (Mintz 1986). Britain led the continent in per capita consumption, with the annual supply rising from less than 2 kg in 1700 to 8 kg a century later and, with new imports coming from India and Africa, to 40 kg by 1900. It changed little a century later, when it was about 36 kg ([FAO 2019](#)).

The American sugar supply rose by nearly two-thirds between 1875 and 1900, to 30 kg/capita. By the year 2000 the country's total supply of sweeteners had more than doubled to about 69 kg/capita and by 2015 it had declined by 15% to about 58 kg. Composition of what the USDA calls “caloric sweeteners” has changed substantially with the rise of high-fructose corn syrup: the share of refined sugar fell from 90% in 1900 to 54% in 2015 and corn sweeteners now provide 45% of the total supply. In contrast, no country in East Asia has shifted toward excessive sugar intakes. Neither China nor Japan has ever sweetened its teas, and the cuisines of

both countries used sugar sparingly in some of their traditional confections. Japanese annual sugar consumption was just 1 kg/capita in 1900 and imports from Taiwan raised it to 16 kg before World War II. Postwar consumption rose from 5 kg in 1950 to nearly 30 kg by 1973, but subsequent decline in demand brought the mean to less than 17 kg by the year 2015 and Japan still derives less food energy from sugar than any other high-income country ([FAO 2019](#)). By 1950 China's per capita sugar supply was no higher than in Japan in 1900 but while post-1980 dietary improvements lifted all categories of food consumption, the sugar supply is still less than 7 kg/capita.

Higher intake of fats has been a universal component of dietary transition. Traditional shortages of cooking oil were particularly trying for poor Chinese families. Given their infrequent eating of fatty pork, plant oils were the only source of dietary lipids. After Mao's death (in 1976) the standard monthly ration was just 500 g/person even in the capital, in provincial cities the rates were between 100 and 200 g, poor peasants had access to as little as 50 g/capita, and oil tickets were issued in denominations as small as 10 and 25 grams ([Smil 2004](#)). For those who never cooked or who think in American volume terms: 25 g are two scant tablespoons and three tablespoons are required for properly stir-frying a vegetable dish, and at least two or three such dishes should be normally prepared for a meal.

Recent annual per capita oil supply is still only between 7–8 kg compared to 15 kg in Japan (after quadrupling since the late 1950s), about 20 kg in France (doubled in 50 years), and more than 25 kg in Italy. Moreover, the Chinese supply of animal fats (mostly lard) is also low (just 2 kg/capita), particularly when the supply is compared to Europe's (mostly butter, 15 kg in France, 18 kg in Germany). Unlike in Europe, a century-long US supply data show a major shift away from animal fats to plant oils: the average butter supply fell from about 6 kg in 1900 to just 2.5 kg by 2015. Concurrently, lard declined from 9 to 0.7 kg, while the cooking-oil supply has nearly tripled since the 1950s to about 30 kg/capita (deep-frying in fast-food restaurants being a major reason for this rise). Assorted meat-based choices are loaded with fat: as already noted, 52% of all food energy in a Big Mac comes from fat, most of it of the saturated variety (McDonald's 2019), and for some frankfurters (hot dogs) the share is around 75%.

Traditional agricultural societies had always consumed a large variety of cultivated vegetables and had always valued many species of fruits. Transitions in their consumption have been taking place on two levels: as increases in quantity and variety of fresh produce because of better transportation and storage; and as shifts in quality. Cold-climate countries have been the greatest beneficiaries of expanded access as intra- and inter-continental imports allowed year-round availability of traditionally seasonal produce and introduced previously unknown species. Their additions have ranged from avocados and mangos to star fruit and lychees, and large North American supermarkets offer more than 30 varieties of fruit.

FAO's global summaries indicate more than a doubling of fruit supplies since 1960 ([FAO 2019](#)). Supplies of fresh fruit have increased much faster than that in newly industrializing countries in East Asia (in China from 4 kg in 1961 to about 75 kg in 2015). Very detailed US data, available only since 1970, show a shift between fresh and processed (mostly canned and frozen) sales, with fresh fruit share rising from 41% to 53% (USDA 2018). US data also show that except for apples, traditional favorites (pears, plums, citrus fruit) have been declining (oranges by half) while tropical fruits are sharply up, as are now constantly available strawberries. Similar shifts have taken place in the European Union and Japan.

Shifts in nutrients

Chemical composition of foodstuffs and digestibility of nutrients became fairly well understood before 1900 ([Atwater and Woods 1896](#)). Russell Henry Chittenden was the first scientist to conclude that sufficient per capita protein intakes should range between 35 and 50 g/day ([Chittenden 1907](#)), and in 1913 Funk posited the existence of a vital amine in food that is able to protect against beriberi ([Semba 2012](#)). This vitamin (thiamine) was isolated in 1926 and all indispensable micronutrients were identified by 1941. Daily requirements for both macro- and micronutrients were subsequently set by expert committees convened in the United Kingdom, in the United States, and later by the UN's FAO, and we now have a good understanding of the optimal ranges of nutrient intakes, as well as of minima compatible with healthy and active life.

Acceptable macronutrient distribution ranges for adults were set by the US National Academy of Sciences between 45% and 65% of all energy

intakes for carbohydrates and 20 and 35% for fats ([Institute of Medicine 2005](#)). The optimum carbohydrate range was confirmed by a study that found a U-shaped association between the share of energy coming from carbohydrates and mortality, with 50–55% of energy from carbohydrate associated with the lowest risk of mortality and both low (<40%) and high carbohydrate consumption (>70%) conferring a greater mortality risk ([Seidelmann et al. 2018](#)). The ranges for dietary fat are, respectively, 30–40% for children 1–3 years of age and 25–35% for ages up to 18. Ranges for protein are 5–20% for children up to three years of age, 10–30% for older children, and 10–35% for adults.

Societies relying on traditional farming always had barely adequate protein supply and deep fat deficits. Even by 1976, the year of Mao Zedong's death, protein's share of China's dietary energy was just 10% and fat supplied only 12% of all food energy, nearly identical to India's share during the early 1960s ([Smil 2004](#)). China's rapid economic rise has lifted protein shares to about 13% and lipids to nearly 30%, reducing the carbohydrate share from almost 80% to less than 60%. India's means, however, are still low, 10% for protein and 19% for lipids, with carbohydrates supplying just over 70% of all food energy, well above the recommended maximum. In affluent societies average protein intakes have been adequate (12–13% of total energy) for generations and the most notable transition has seen the rising share of lipids. Reliable reconstruction of nutrient shares in the US food supply shows protein shares rising only marginally, from about 11% during the second decade of the 20th century to 12% at its end, while during the same time period the lipid share increased from 32% to 40%, well above the desirable maximum ([Gerrior et al. 2004](#)). Similarly, in France lipid share rose from about 25% of all energy right after World War II to just over 40% in the second decade of the 21st century.

Increased lipid share was accompanied by a shift between plant and animal sources. Plant lipids come as polyunsaturated fatty acids in seed oils (soybeans, sunflowers, omega-6 acids) as well as by fish (omega-3 acids), and as monounsaturated acids from olives, rapeseed, peanuts, and avocados. Animal fats are made up mostly of saturated fatty acids, eaten either as pure solids (butter, lard) or in meat and dairy products. During the 20th century the average American per capita fat supply was up by more than 40%, saturated fats rose by only about 10%, and monounsaturated fats were up by more than 60%, while the supply of polyunsaturated fats had nearly tripled

([Gerrior et al. 2004](#)). Switching from animal fats to corn and soybean oil was motivated by consensus recommendations aimed at reducing cardiovascular mortality. In 1900 butter supplied about 14% of all dietary fat and lard about 12%; a century later both shares were down to just 3% as per capita butter supply fell from 8 kg in 1909 to just 2.5 kg in 2015 and as fat-reduced and skimmed milk came to dominate American consumption (USDA 2018).

Notable increases in vitamin supply included nearly tripling of vitamin E and roughly doubling of thiamine, riboflavin, and total folate, while average levels of vitamin C rose only slightly. Among minerals calcium has been up by some 30% (more dairy foods), iron by two-thirds (more meat), and sodium by a third (more processed food). Sources of dietary fiber have changed (with less staple grain and more vegetables and fruit), but there has been no significant overall shift in its average daily per capita supply.

Consequences and Concerns

No other outcomes of nutritional transition have been more important than the elimination of famines and reduction of undernutrition, and all populations have benefited from an unprecedented availability of affordable foodstuffs. Shares of disposable incomes spent on food have been declining, while the variety of fresh foods, beverages, and prepared foods has grown to excessive and wasteful levels. Dietary combinations, influences, and cross-currents might be easier to defend—why should great Indian or Japanese dishes remain confined to their countries of origin?—but this internationalization and globalization of tastes has brought its own problems (just think of the relatively sudden rise of sushi to a global food choice and its implications for overfishing and aquaculture). Most notably, and most unfortunately, great achievements of agricultural and nutritional transitions have been accompanied by increased generation of food waste as well as by excessive eating and by a relatively high prevalence of new unhealthy diets that have contributed to the rising occurrence of obesity. Critical looks show that some nutrients have been rightly implicated in these shifts but others have been undeservedly maligned and are now finding new acceptance.

Ending famines and reducing undernutrition

Ending the long history of famines is an achievement that is usually absent from the lists of fundamental modern advances that are disproportionately dominated by technical inventions in general and electronic devices in particular. In Europe (excluding Russia), threats of recurrent famines and severe chronic malnutrition were eliminated already during the early stages of agricultural transition ([Alfani and Ó Gráda 2017](#)). As a result, the Irish famine of 1845–1849 was the last event that could be attributed in a large degree to failed harvests ([Woodham-Smith 1992](#)). Russia's last peacetime famine was in 1891–1892 but subsequently the Russian Empire became a major exporter of wheat.

Major famines in the USSR (1921–1923 along the Volga, Ukrainian *Holodomor* of 1932–1933, and a brief famine in summer of 1947) were the result of violent conflicts or the consequences of destructive policy decisions (including Stalin's deliberate attempt to starve the Ukrainian population to submission)—not of any inherent inability to produce enough food ([Klid and Motyl 2012](#)). And the months of severe malnutrition and famine in parts of the Netherlands (*Hongerwinter* between October 1944 and May 1945) were caused by the Nazi blockade of food shipments ([Stein 1975](#); [Hart 1993](#)).

The world's worst famine, in China between 1959 and 1961, was not a result of natural catastrophes but of deranged Maoist policies ([Dikötter 2010](#); [Yang 2012](#)). After tens of millions died it became clear that a swift agricultural transition was imperative, and that is why I believe that the proximate reason for China's opening to the West (beginning with Nixon's trip to Beijing in 1972) was to gain access to the most advanced process of ammonia synthesis and use the increased fertilizer output to boost the yields and preempt the threat of famine ([Smil 2004](#)). The first commercial deal following Nixon's trip was China's order of 13 of the world's largest and most modern ammonia-urea complexes from M.W. Kellogg of Texas. Otherwise the country would have soon faced a prospect of another famine but “because it acquired the means to break through nitrogen barrier, China's population is now fed better than at any time during its long history” ([Smil 2004](#), 116)—in fact its average per capita food supply is now higher than Japan's.

India had its last famine in Bengal in 1943, before the adoption of high-yielding short-stalked wheat and rice varieties secured adequate harvests and enabled the country to cope successfully with regional droughts (1966–1967 in Bihar, 1972 in Maharashtra, 1979–1980 in West Bengal) without any major loss of life. To be sure, elimination of famines has also required better-organized state response, better communication and transportation capabilities, and, as [Sen \(1981\)](#) stressed, accountability brought by democratic institutions—but only adequate food production was able to provide necessary and enduring buffers against major downturns of supply. The only part of the world where the threat of recurrent famines remains a threat is sub-Saharan Africa, the region that is still in the earliest stages of agricultural transition and where farm production is also repeatedly endangered by violent conflicts.

Elimination of malnutrition and undernutrition is, in some ways, more challenging than putting an end to famines. Micronutrient malnutrition could be addressed once we have identified vitamins and minerals responsible for diseases caused by micronutrient deficiencies ([Mozaffarian et al. 2018](#)). Xerophthalmia (vitamin A), beriberi (vitamin B1), pellagra (vitamin B3), pernicious anemia (vitamin B12), scurvy (vitamin C), rickets (vitamin D), goiter (iodine), osteoporosis (calcium and phosphorus), and anemia (iron) could be treated by fortifying staple foods with specific micronutrients. Nearly all white flour is now enriched with iron and four vitamin Bs (thiamin, niacin, riboflavin, and folic acid). But even in affluent countries some population subgroups have widespread micronutrient deficiencies. In the United States about 30% of the population has at least one vitamin deficiency or anemia, with the rates as high as 55% among blacks, 40% in low-income households, 39% among obese individuals, and 37% among women ([Bird et al. 2017](#)).

Undernutrition in many low-income countries is not due to inadequate supply but to uneven access to food, as well as to poor parental care stemming from the lack of basic education and nutritional knowledge. The global trend has been going in the right direction. Numbers of undernourished people are calculated in FAO's Rome headquarters by using assumptions and modeling that may significantly overestimate food energy requirements of well-nourished people and hence the shares of the malnourished population ([Piers and Shetty 1993](#); [Smil 2000a](#))—but there is also concern that they may underestimate the real total.

The FAO's estimates of the worldwide share of undernourished people have declined from about 65% in 1950 to 25% by 1970, and about 15% by the year 2000; continued improvements lowered the rate to the historic low of 10.4% (777 million people) in 2015 followed by a slight uptick to 11% (815 million) in 2016 ([FAO 2017a](#)). This reduction, from two-thirds to only about one-tenth of the global population, is another impressive illustration of an existential shift that has not received sufficient recognition, particularly when that shift is compared to those incessant professions of admiration and awe reserved for ephemeral electronic toys and for such “disruptive innovations” as repackaging Chinese manufactures into American cardboard boxes and selling them on Amazon.

Rising per capita intakes of animal foodstuffs have provided more protein during childhood and adolescence and have resulted in taller bodies, first in North America, Europe, and Japan, and later also in many countries of Latin America and Asia. As malnutrition and stunting were eliminated, average heights for every age group kept rising (NCD Risk Factor Collaboration 2016). As already noted, the largest height increments were registered in Asia, and Japanese data also show how sensitive this key anthropometric variable is to any deterioration of the food supply. The average height of ten-year-old boys rose from 123.9 cm in 1900 to 129.7 cm in 1940 (gaining about 0.15 cm/year) but wartime food shortages reduced it to 126.1 cm by 1946 (−0.6 cm/year). Because of continuing postwar food shortages and severe rationing, the growth resumed only in 1949 and by the year 2000 ten-year-old boys averaged 139.1 cm after gaining 0.25 cm/year for half a century (SB 2006).

Affordability and variety of food

In Europe, North America, and Australia agricultural transition had eliminated the worst forms of malnutrition already more than a century ago. Thanks to scientifically based food rationing, Britain was able to maintain that discipline even during nearly six years of WWII economic mobilization ([Zweiniger-Bargielowska 2000](#)). Food rationing in the United Kingdom (and in several other European countries) lasted until 1954, but as the postwar economies began to prosper, agricultural transition resulted in more affordable access to a much wider variety of foods as well as a greater

convenience in buying, storing, and preparing it. These have been universal trends; only their timing has differed.

Affordability is easily traced by the share of disposable income that an average household spends on food. Relationship between income and family expenditure on food was defined by Ernst Engel, a German economist and statistician, more than one-and-a-half centuries ago: “Je ärmer eine Familie ist, einen desto grösseren Antheil von der Gesamtausgabe muss zur Beschaffung der Nahrung aufgewendet werden” (the poorer a family, the greater share of its expenditure must be spent on the procurement of food) ([Engel 1857](#), 28). This relationship has been applicable to every modernizing society. But Engel’s law refers only to the share of disposable income: the total amount spent on food is actually rising in richer households and in affluent societies, but its share of the total expenditure is falling.

During the late 19th century it was not uncommon for many poor working-class urban households to spend 60% of their disposable per capita income on an adequate diet. In 1900 the US share in large cities was about 43%, by 1950 it was reduced to 20%, and since the year 2000 it has been below 10% (BLS 2006; USDA 2018). Only a few countries have a similarly low expenditure, but declines in the share have been the global norm. Among richer EU countries the share is down to 10–15%, in Latin America it is mostly around 30%, in China the share dropped from more than 60% (with all food rationed in cities) during the 1970s to 33% in 2015, and the Indian mean is now about 35%.

A transition within this transition has seen an increasing share of income spent on eating out. In the United States in 1900 that share was well below 10%, by 1950 it was about 20%, but by 2015 it was about 40%, with many urban families now spending more on eating out than on eating at home. Deliveries of restaurant food have had a significant niche of urban lunch and dinner markets (sushi in Japan and pizza in the United States being two common examples) that has grown with mobile-phone-mediated delivery services. And there is a new category of meal-kit options with portioned ingredients and with accompanying instructions (companies such as Plated, Blue Apron, Sun Basket, and Green Chef) delivered to be cooked at home ([Leonhardt 2017](#)).

Higher affordability has been accompanied by increasing diversity of foodstuffs. Even when they contained sufficient energy and provided

essential nutrients, typical diets in many well-off countries were monotonous. In non-Mediterranean Europe they were dominated by bread and by such coarse grains as oats and barley, and starting in the 16th century also potatoes, usually eaten in soups and stews with little distinction between the composition of the three (or just two) daily meals. Asian diets often included more, and a greater variety, of vegetables but with less meat, and in East Asia without any dairy foods even a higher share of food energy came from plants. I have already noted the variety of fruits that are now on everyday display in supermarkets of all continents. Analogical expansion of choices has taken place in other food categories from cereals (now including quinoa and tef) to processed meats (*jamón ibérico*, *prosciutto*).

Successive waves of non-Western cuisines were first sampled in often less-than-authentic restaurants—epitomized by such Chinese-American creations as beef and broccoli, orange chicken, and fortune cookies (Fullerton 2017)—and had eventually entered the mainstream choices. In the United States the non-European cuisines that have been absorbed, adapted, and mainstreamed (to different degrees) include Mexican foodways, ubiquitous Chinese cooking, and recently much expanded Indian, Japanese, Korean, and Thai offerings. In the United Kingdom the greatest influence comes with Indian/Bangladeshi/Pakistani dishes; continental Europe has strong incursions of Turkish, Lebanese, Indian, Chinese, and Thai cuisines. These dietary invasions and domestications have been an important part of coming to terms with the “others” in societies experiencing rapid globalization, particularly those that were until recently fairly insular.

Food waste, obesity, and civilizational diseases

All affluent countries have been producing substantially more food than could be possibly eaten even by frankly gluttonous populations. Average daily per capita rates are now, with the sole exception of Japan, in excess of 3,000 kcal, with more than 30% (and even more than 40%) of all food energy originating from lipids, with dietary protein far in excess of daily needs (highest rates up to 120 g/day, with 55–65% coming from animal foods) and with annual meat consumption generally exceeding average body weight (70 kg) and, in terms of carcass weight, even surpassing 100 kg/capita (FAO 2019).

Food production is the single largest activity putting humans into competition with other species inhabiting the biosphere and hence it is particularly destructive to produce food that will be wasted. Food balance sheets put the recent American food supply as high as 4,000–4,200 kcal/capita (USDA 2018). Only tall, well-muscled, and hard-working adult males (think of lumberjacks or miners) would need to eat that much. Adjustments for “spoilage and other waste” applied by the USDA reduce the average daily supply to about 2,600 kcal/capita. But even this rate, 35% lower than the gross supply, is still excessive as a population-wide mean of actual consumption, as it is far higher than the needs of very young and very old (many women over 75 years of age may need fewer than 1,500 kcal/day).

Recent recall-based US studies of daily food consumption ended up with a population-wide (all people older than two years) mean of about 2,100 kcal/capita (NHANES 2014). With an average supply of at least 3,600 kcal/capita the result is a daily food waste of 1,500 kcal/capita. This is an astonishingly high waste that could be dismissed by pointing out the well-known inaccuracy of dietary recalls—but there is another way to confirm the large gap: to calculate specific metabolic requirements by using physiological models that relate body weight to the amount of food eaten (Hall et al. 2009). Applying such a model to the US population found a slight increase of food actually eaten, from about 2,100 kcal/day in 1974 to 2,300 kcal/day in 2005.

But during those three decades average per capita food supply rose from about 3,000 to 3,700 kcal/day and hence average food waste increased from 28% of the retail supply in 1974 to about 40% three decades later, when it averaged more than 1,400 kcal/day. In 2017, with 325 million people, this amount of wasted food energy could have provided adequate nutrition (assuming 2,200 kcal/day) for just over 200 million people: that is, almost exactly the entire population of Brazil, the world’s fifth most populous nation.

British surveys found that waste adds up to about 21% of all food purchased by households, with specific rates that include 40% for vegetables and 20% for meat and fish (WRAP 2018). Some items, including sausages, bacon, and meat-based ready-to-eat and takeout meals are often thrown away unopened. And a Canadian study came with the highest published loss-and-waste estimate: 58% of all food produced (total

of 35.5 Mt/year) with 34% of the total during processing and 24% during production (Nikkel et al. 2019). Revealingly, the study shows that 32% of this loss and waste could be rescued for consumption. Japan has been the affluent world's most frugal food consumer and as its population ages the actual average per capita intake has fallen below 2,000 kcal/day (Smil and Kobayashi 2011). Even so, with the food supply at about 2,500 kcal/capita this average still prorates to retail and household food waste of at least 25%.

An FAO study concluded that annual losses in Europe and North America prorate to about 100 kg/capita (Gustavsson et al. 2011). In 2018, with the combined population of about 860 million people in the European Union, the United States, and Canada, that would amount to nearly 90 Mt/year. Specific food waste rates for major food categories range from more than 10% for meat to 25% for grains and 20–30% for vegetables—but, as previously explained, behind every unit of wasted chicken or pork meat there are at least 3–5 units of wasted plant feed! Moreover, environmental damage due to nitrate leaching, excessive soil erosion, or antibiotic resistance attributable to wasted food is compounded by the necessity of dealing with large volumes of material that cannot be easily recycled because a large share of food waste is now commingled with paper, metal, glass, and several kinds of plastic.

In contrast, food waste in low-income countries is still largely caused by inadequate storage. As a result—and despite lower rates of overall supply and much lower per capita consumption of meat and dairy—typical food losses in low-income countries are of the same magnitude as in affluent nations. Given the scale and complexity of the entire food system, it would be quite unrealistic to believe that food losses can be reduced to rates in low single digits—but, at the same time, there is no justification for tolerating any losses in excess of 20% or 25%.

Even after large-scale losses too much remains to be consumed and to contribute to the recent wave of obesity. This condition, now increasingly starting in childhood, is not a metabolic inevitability; it can be directly traced to a combination of ignorance regarding healthy eating, deliberate (often compensatory) overeating, and preference for sedentary life styles. Body mass of any population is normally distributed and hence there will be always people whose weight will be far above the mean value—but there is no validity to the claim that the mean itself must be expected to rise. US data show that the rise of obesity has not been a simple function of rising

food supply but, overwhelmingly, a matter of choice, a combination of overeating, and inadequate activity ([Figure 3.4](#)).

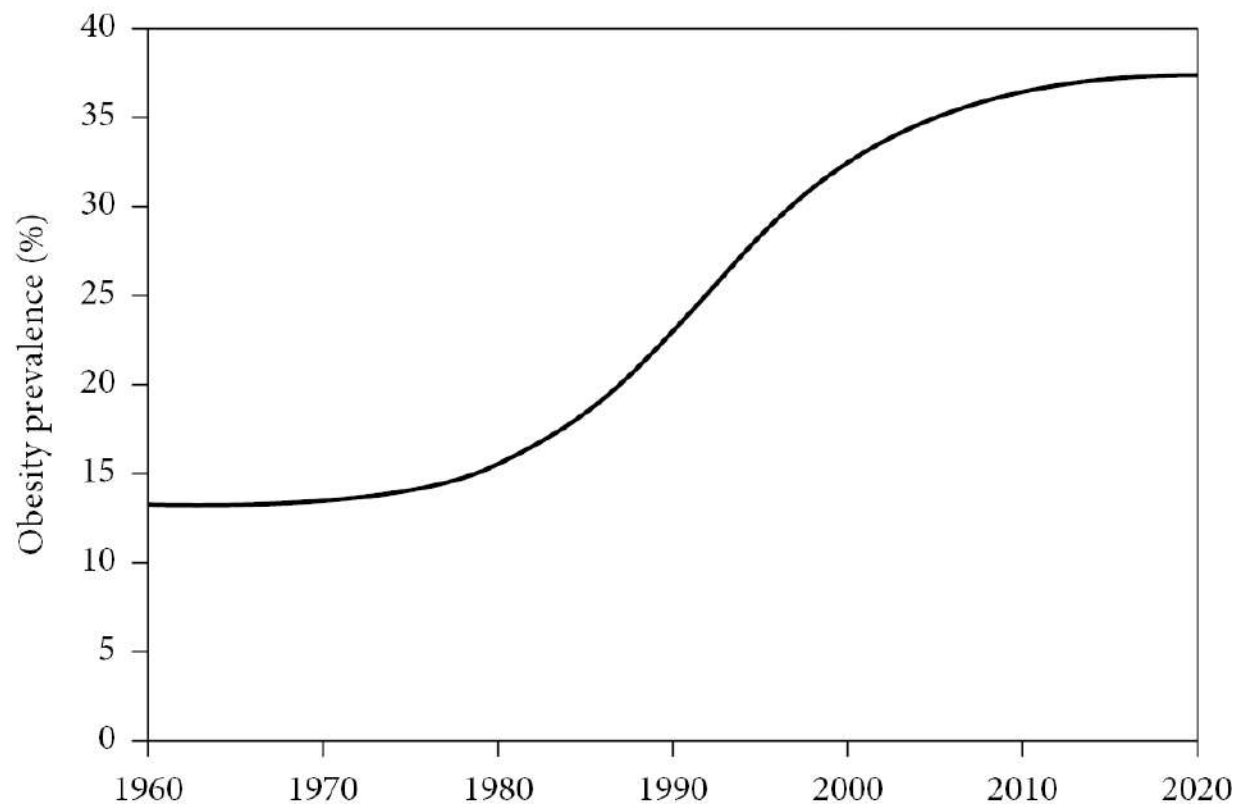


Figure 3.4 Prevalence of obesity (body mass index between 30 and 35) in the United States was stable until the late 1970s. Subsequently, it has doubled but a logistic fit points to the asymptotic value of about 38% of the total population. Plotted from data in [Ogden et al. \(2012\)](#) and [Trust for America's Health \(2017\)](#).

To make the point, it is first necessary to realize that normal weight is defined as body mass index ($BMI = \text{kg/m}^2$, the quotient of weight in kilograms and height in meters squared) between 19 and 25 (NIH 2019). Overweight people have BMI between 25 and 30, and BMI above 30 signifies obesity. After World War II the share of the US population with $BMI > 25$ remained steady until the late 1970s, with the overweight share at a third and obese share at less than an eighth of the population. By the century's end excessive intake and decline in daily activity caused an epidemic of obesity: the share of obese adults had more than doubled and by 2010 it rose to nearly 36%, including 5% of extremely obese ([Ogden et al. 2012](#)). With almost the same share of adults being overweight three in four American adults now have abnormal BMI and this unmistakable

rotundity is evident in all public spaces. Moreover, obesity now begins at earlier ages, with the shares of overweight and obesity now above 50% both for children 6–11 years old and for youth between 12 and 19 years, and with even higher shares among lower-income groups. This increase is particularly worrisome because childhood obesity commonly becomes a lifelong condition.

But America, although still the unenviable obesity leader, now has some close runners-up: combined overweight and obesity ratios for adult men are now above 60% also (in descending order) not only in tiny Kuwait and Qatar but also in Australia, Mexico, the United Kingdom, Germany, the Czech Republic, and Portugal, and among adult females obesity shares higher than 50% are in all of the previous countries as well as in South Africa and Morocco ([World Obesity 2018](#)). And the worldwide trend has been going in the wrong direction: between 1980 and 2008 adult BMI had increased in all but eight of the world's 200 countries, and the globally standardized BMI averages rose to about 24 for both men and women. The total of obese children and adolescents has increased tenfold in four decades to reach 124 million by 2016, when a further 213 million were overweight (WHO 2017). Continuation of this trend would see the worldwide number of obese children surpassing that of undernourished youngsters as soon as 2022.

Finally, a brief look at nutrition's role in the prevalence of cardiovascular diseases (CVDs) and diabetes, two leading causes of mortality that have been linked to nutrition. [Archer et al. \(2018\)](#) firmly believe that since the 1960s all large-scale diet-disease studies that relied on dietary recalls (and hence failed to measure actual food intakes) have engendered a fictional discourse. Memory-based assessment methods are unreliable and unverifiable, and credulousness is obviously antithetical to any scientific inquiry. And yet such methods have been used by thousands of studies to collect data on millions of individuals, and thus “contrary to current conjectures, there are no valid data demonstrating that ‘diet’ per se is causal to increased mortality from obesity, NCDs, and metabolic diseases” ([Archer et al. 2018](#), 105). This might be an excessively sweeping conclusion, but reversals of consensus regarding diet-disease links make clear that the available results are questionable.

The Framingham Heart Disease Epidemiological Study was the most prominent source of identifying the intake of saturated fat and cholesterol in

meat, eggs, and dairy products as a very important, even the decisive, contributor to the rise of cardiovascular mortality in the Western world (Kannel et al. 1961; Keys 1980; Castelli 1984). Rees (1983, 23) concluded that “there is no doubt that diet and diet alone is responsible for the vast majority of all coronary heart disease in Western society.” In 1957 the American Heart Association recommended lowered fat intake as the best way to reduce the incidence of coronary heart disease (AHA 1966). Subsequently, Ancel Keys became the leading promoter of the low-fat Mediterranean diet (Keys and Keys 1975).

These findings led to a widespread advocacy of low-fat diets for all Americans. Between 1968 and 1987 all major recommendations concerning diet and coronary heart disease advocated that dietary shift (Truswell 1987). American, Canadian, and European dietary guidelines for adults older than 20 years recommended that fat intake should remain below 30% and saturated fat consumption below 10% of total food energy, and that daily cholesterol intake should not exceed 250–300 mg. La Berge (2008, 139–140) chronicled in detail how this

low-fat approach became an overarching ideology, promoted by physicians, the federal government, the food industry, and the popular health media . . . even though there was no clear evidence that it prevented heart disease or promoted weight loss. Ironically, in the same decades that the low-fat approach assumed ideological status, Americans in the aggregate were getting fatter, leading to what many called an obesity epidemic. Nevertheless, the low-fat ideology had such a hold on Americans that skeptics were dismissed. Only recently has evidence of a paradigm shift begun to surface.

Even at the high point of this low-fat/no-fat advocacy, there was plenty of epidemiologic and demographic evidence that made it impossible to conclude that “these interventions alone will result in major declines of cardiovascular mortality” (Smil 1989, 400), and serious doubts remained if it can provide a sound and solid basis for efficacious dietary guidelines for entire populations. As we have seen, consumption of lipids has undergone a very substantial transformation both in terms of quantity (declines for all animal lipids) and quality (shift from saturated to poly- and monounsaturated fats) but the latest studies of this complex link confirm that there are no strong, universal causal links between diet and heart disease, and, more specifically, that the intake of saturated fats is not associated with all cause mortality, CVD, chronic heart disease, ischemic stroke, or type 2 diabetes (de Souza et al. 2015).

The most comprehensive meta-study of links between the consumption of saturated fats and heart disease (it examined 72 unique studies, both observational and prospective controlled trials, including 42 in Europe and 19 in North America) concluded that “the pattern of findings from this analysis did not yield clearly supportive evidence for current cardiovascular guidelines that encourage high consumption of polyunsaturated fatty acids and low consumption of saturated fats” ([Chowdhury et al. 2014](#)). Moreover, a study measuring biomarkers of dairy fat and total and cause-specific mortality in nearly 3,000 older US adults found that long-term exposure to circulating phospholipid pentadecanoic, heptadecanoic, or trans-palmitoleic acids (present in dairy products) was not significantly associated with total mortality or with incidents of CVD but that “high circulating heptadecanoic acid was inversely associated with CVD and stroke mortality and potentially associated with higher risk of non-CVD death” ([Otto et al. 2018](#)).

Again, a reversal of former conclusions but one that also recognizes the complex nature of the exposure: heptadecanoic acid appears to be CVD- and stroke-protective but its long-term presence carries a potentially higher risk of non-CVD death. And another, more specific link between fatty acids and CVD is now in doubt. Higher intakes of omega-3 polyunsaturated fatty acids from oily fish, as well as of alpha-linolenic acid from plants, were advocated to lower the risks of cardiovascular events. But the most extensive meta-analysis of relevant studies shows, with a high degree of confidence, that higher intakes of these acids have little or no effect on overall mortality as well as on cardiovascular events, and that they probably make little or no difference to cardiovascular death, coronary deaths, stroke, or heart irregularities ([Abdelhamid et al. 2018](#)).

There is less uncertainty as far as the prevalence of diabetes and increased sugar consumption are concerned. Causes of type 1 diabetes are unknown but the risks of developing the disease are increased by the presence of several gene variants ([Chatterjee et al. 2017](#)). Type 2 diabetes also has a genetic-familial component and an association with aging, but its onset, progress, and severity can be greatly influenced by diet and lifestyle, above all by frequent consumption of sweet drinks and by overeating and inactivity leading to obesity. Abandonment of traditional (low-fat, complex carbohydrates) diets in favor of high-energy, high-sugar diets that include more processed foods are, together with more sedentary lifestyles, leading

nongenetic contributors to the rising prevalence of type 2 diabetes (Soto-Estrada et al. 2018).

In 2015 about 415 million people had diabetes, with type 2 accounting for more than 90% of all cases and with projections for more than 640 million cases by 2040 ([Chatterjee et al. 2017](#)). In the same year just over 30 million Americans (or nearly 10% of the total population) had diabetes (including more than 7 million who remained undiagnosed), with type 2 accounting for 95% of the incidence ([CDC 2017](#)). Randomized controlled studies in Asia, Europe, and the United States indicate that dietary and behavioral intervention (reducing intake of total energy and sweetened drinks in particular, exercising more) in individuals with prediabetes can reduce the disease's onset by 30–60% ([Pan et al. 1997](#); [Tuomilehto et al. 2001](#); [Alouki et al. 2016](#)). Unfortunately, when [Siegel et al. \(2018\)](#) studied American adults without type 2 diabetes to find out how many engage in lifestyle behaviors that are known to reduce the risk of type 2 diabetes they found that only about 3% of individuals met the majority of type 2 diabetes risk reduction goals.

Environmental degradation

Expansion of agricultural production and its far from globally completed intensification have aggravated some long-standing problems (soil erosion in arid regions, leaching of nitrates) and have caused new environmental concerns ranging from the impacts of large-scale crop monocultures to the risks of soil contamination with heavy metals. Crop and animal farming have been also major sources of biodiversity loss and emissions of greenhouse gases: these impacts will be considered in the chapter on environmental transitions. The most obvious environmental marker of agricultural transition has been the vast expansion of agricultural land.

Our best reconstructions of past aggregates show that the world's agricultural land (arable land and permanent crops) had nearly sextupled in two centuries, from about 260 million ha in 1700 to 1.5 billion ha in the year 2000, with further slow growth afterwards ([FAO 2019](#)). The first major expansion epoch was during the latter half of the 19th century (conversions of grasslands, mostly in North America, Argentina, and Russia); the second one took place since 1950 (led by tropical deforestation in Asia, Africa, and Latin America). Land used for pastures has expanded even faster, sevenfold

since 1700 to about 3.2 billion ha, with most of the recent gains coming, again, from large-scale tropical deforestation ([FAO 2019](#)). The land devoted to croplands and pastures has now reached more than 4.8 billion ha, or nearly 40% of the world's ice-free surface, only slightly less than the combined area of North America and Africa.

Given this grand total, even those specific environmental problems that affect only small fractions of all food-producing land have had extensive impact. This reality is easily illustrated with data on monocultures or soil erosion. Monocultures are increasingly taking over larger shares of all planted land and in the largest crop-producing nations their aggregate extent equals and surpasses not only the areas of many small states but even of some of the world's major populous countries. On the Canadian Prairies, formerly dominant wheat has been displaced by rapeseed (canola), and a similar shift has taken place in parts of Western Europe ([FAO 2019](#)). At 35 million ha the area now planted to corn in the United States is nearly as large as Germany and the areas growing American and Brazilian soybeans (each about 33 million ha) are equivalent to those of Malaysia or Vietnam, with many large contiguous fields having in excess of 1,000 ha (10 km²). Moreover, in Brazil many of these fields occupy deforested land as a mega-scale monoculture replaced some of the world's most diverse plant and animal communities.

Soil erosion is a chronic challenge for farming ([Follett and Stewart 1985](#); [Wicherek 1993](#); [Godone and Stanchi 2011](#)). Its prevalence has increased with the cultivation of row crops: before their canopies close, the planted soil is open to rain's direct erosive action. Compaction of agricultural soils (affecting water infiltration retention and root development, increasing erosion rates and lowering crop yields) has become more common with the use of heavier machinery and with more after-seeding passes over a field to apply fertilizers and pesticides. Losses of organic matter—whose high content is vital for providing carbon to feed soil fauna, earthworms above all—follow reduced use of animal manures or elimination of regular rotations with leguminous crops (that were plowed in after growing for two to three months) and often exclusive reliance on increasing doses of synthetic fertilizers.

Contamination of agricultural soil and crops with heavy metals (notably cadmium, released from smelters) has become a major concern in some densely populated parts of China, above all in Hunan but also in Sichuan

and Guangxi (Zhao et al. 2015; Liu et al. 2016). This problem is made worse by high acidity of many soils (it increases cadmium's solubility); moreover, soil acidification (largely driven by the country's enormous emission of SO₂ from coal combustion) has been progressing and further declines of pH could pose uncommon risk to people consuming rice grown in heavily acidified areas. Even when the concentrations of the metal remain below the admissible level, cadmium contamination lowers rice yield and grain quality (Li et al. 2017).

A new and intractable problem has emerged in recent decades with the adoption of crop cultivation under thin (<20 µm) polyethylene films. These films are spread in arid and colder regions to create plant microclimate, reduce water losses (cutting demand commonly by 20–30%), prevent weeds and pests, and increase yields. But thin plastic is easily torn, it is not biodegradable, it is not generally recycled, and its shredded bits add up to tens to hundreds of kilograms per hectare in the top 30 cm of soil (60–260 kg/ha). Yields of wheat and cotton are progressively lowered as the residual material in soil accumulates and as plastic bits alter soil structure, damage soil fauna, and interfere with plant germination. Recycling of this plastic is difficult because it is torn and coated with dirt; obviously, thicker films would last longer and would be easier to retrieve.

Polyethylene contamination is now common in scores of countries, but China has the largest area of such plastic-covered fields: by 2011 about 1.2 Mt of polyethylene were used to cover nearly 20 million ha, or about 15% of the country's cultivated area (Yan et al. 2014). Plastic films also release phthalates (common plasticizers) whose levels in Chinese soils are now usually at the high end of the global range, and are mostly higher than allowable concentrations (Lü et al. 2018; Li et al. 2016). In China about 20% of arable land is already contaminated with different kinds of toxins whose concentrations exceed national standards.

Ground cover is not the only use of polyethylene films in cropping. Thicker films are also used to create plastic greenhouses for hydroponic cultivation of vegetables. The world's highest concentration of these temporary shelters, visible on satellite images, is in Spain's Almería province (Figure 3.5): with the exception of roads and a few small settlements the southernmost tip of Almería is under 450 km² plastic to produce a major share of the European Union's winter vegetables by using cheap migrant labor (NEPIM 2019). Besides the obviously large mass of

torn plastic waste and enormous water demand in an arid region this extensive plastic cover also increases the region's albedo.



Figure 3.5 Plastic greenhouses cover virtually all available land south of the highway A7 in Andalusia, Spain. For scale, the length of the highway shown in the satellite image (running from WSW to ENE) is about 35 km. Astronaut photograph ISS008-E-14686, February 7, 2004, NASA.

Soil contamination becomes, gradually or rapidly, water contamination and, again, agricultural transition elevated long-standing problems to unprecedented scales. Leaching of nitrates (from animal stalls, manure piles, and applied liquid organic fertilizers) and contamination of water wells, ponds, and streams was a common problem in traditional intensive farming, but one with clearly limited localized impact. As the scale and intensity of fertilization increased, nitrate leaching became a concern not only in the regions receiving high applications of nitrogenous fertilizers but also far downstream, as it has eventually led to the creation of extensive coastal dead zones.

Inputs of nitrogen and phosphorus cause eutrophication, which promotes algal growth, and the enhanced photosynthesis increases the output of degradable biomass to bottom waters, where its decomposition consumes

oxygen and creates hypoxic or anoxic zones that are unable to support marine life (Breitburg et al. 2018). Major dead zones are now found in the Gulf of Mexico (the largest contiguous dead zone in North America), along the US Atlantic coast, in Northwestern Europe from France to the Baltic Sea, in Southern Japan, and in the East China Sea. Other water contaminants originating in farming include pesticide residues and antibiotic residues in animal wastes (Van Epps and Blane 2016). Concentrations of large numbers of cattle, pigs, or poultry in CAFOs have created particularly great challenges for managing their waste water output.

Long-distance transport of cooled and refrigerated foodstuffs has added to agriculture's considerable generation of greenhouse gases. Even when we leave aside intercontinental shipments of fruits, vegetables, meat, and dairy products, typical transportation distances within North America and the European Union are considerable: about 4,500 km for vegetables from California to New England and nearly 4,000 km for Mexican mangoes and avocados from Michoacán to Manitoba, while European shipping distances are 3,500 km for peppers or strawberries from Almería to Stockholm and more than 3,000 km for Calabrian tomatoes to Scotland.

Agriculture is also a significant contributor to the global emissions of greenhouse gases (CCAFS 2019). CO₂ is released because of the land-use changes (conversion of natural ecosystems to fields and pastures), from soils during cultivation and from the decomposition of crop residues and of soil organic matter. CH₄ originates mainly from the enteric fermentation of ruminant animals and also from rice cultivation (from waterlogged anoxic soils) and from anoxic decomposition of organic matter. N₂O is emitted mainly from applied synthetic fertilizers as well as from the decomposition of manures and crop residues.

None of these fluxes can be measured with high accuracy (CH₄ emissions from livestock and N₂O emissions from soils are particularly variable) and hence the overall share of greenhouse gas emissions from agriculture is best expressed as a range: it is most likely between 20% and 30% of the total flux of greenhouse gases, largely thanks to the fact that the two major gases, methane and nitrous oxide, are much more effective absorbers of the outgoing radiation. At the same time, proper management of croplands and pasture can make them significant sinks of CO₂ in soil organic carbon.

4

Energies

Without rising direct and indirect use of fossil energies and primary electricity there could have been no substantial gains in crop and animal productivities and in affordability and variety of nutrition—and fossil fuels and electricity had the same transformative impact on all human activities, be it on the productivity of industrial processes, on the speed and comfort of all new modes of transportation, or on the ways people spend their leisure time. Economic implications of this dependence (profound changes of labor markets, impressive gains in manufacturing productivity, shifts from primary and secondary economic activities to services, increases of national economic product and of per capita incomes) will be detailed in the next chapter. In this chapter I will focus on the three principal components of energy transitions: the rapid shift from phytomass to fossil fuels and from animate to inanimate prime movers; the electrification of modern societies (an even more transformative development than the combustion of fossil fuels); and an increasing variety of energy uses. These shifts have been accompanied by impressively improving conversion efficiencies and declining energy intensities—but we still produce too much waste.

Energy Transitions

Once again, there is strong contrast between the stagnation and only a very slow rate of improvements during the millennia preceding industrialization and rapid changes beginning during the second half of the 19th century. Reliance on inefficiently used biomass fuels (wood, charcoal, straw, dried dung) as the only sources of heat was the most obvious universal feature of this stagnation. Combustion of these fuels was done in open fires or in inefficient fireplaces and simple stoves, wasting typically more than 90% of energy and creating high levels of indoor air pollution. This pollution keeps

on affecting more than two billion people in low-income countries that still rely on such arrangements for cooking ([WHO 2018b](#)). Use of charcoal (nearly pure carbon and hence a smokeless fuel more suitable for indoor uses) had greatly lessened these exposures but its higher cost limited its use.

England had an exceptionally early start in shifting from phytomass to coal: its transition began already during the 16th century. Other European countries and the United States followed only 200–250 years later and coal remained their new dominant source of primary energy for less than a century as fuels refined from crude oil, later supplemented or displaced by natural gas, gained larger shares of energy market. Some countries have not followed the dominant sequence from wood to coal and from coal to hydrocarbons and primary electricity, and went from traditional biofuels directly to hydrocarbons; others became highly dependent on hydroelectricity.

Still, the sequence of wood-coal-oil-natural gas has been the dominant one; however, there were notable differences in the provision of mechanical energy. Human labor was its only source in the earlier stages of evolution but in some societies domestication of animals began to change that situation more than seven millennia ago. With improved harnessing and better feeding, draft animals had eventually supplied a major share of kinetic energy in some agricultural societies. And many Old World societies had also harnessed the kinetic energy of running water and wind.

From wood to coal

Plants were the only source of heat during tens of thousands of years of foraging existence, as well as during the nearly 10,000 years of traditional agricultural societies. Woody biomass had always dominated; charcoal made from wood by pyrolysis and various crop residues supplemented the supply, or were the only meager source in deforested regions. The most notable exception to the most common transition from wood to coal was the Dutch Republic during its Golden Age (1608–1672), energized by a combination of peat and wind power (de Zeeuw 1978; [Unger 1984](#)). But once the best peat deposits had been largely exhausted the country turned to coal.

Accomplishments of this first energy transition are best appreciated by understanding low per capita use of wood in traditional societies. By 1800

average per capita supply of fuelwood was just 7 GJ (less than 500 kg of wood) in Germany, about 9 GJ in France, but more than 35 GJ in Sweden ([Kander et al. 2013](#)). There were substantial regional variations, and large cities consumed more. Paris in 1818 used an average 1.43 m³ of wood, 226 liters of charcoal, and 57 liters of coal per capita. With standard conversions this quantity equals about 20 GJ/year, with wood supplying about 16 GJ/year, or twice the countrywide mean at that time ([Dupin 1827](#)). A metric ton of iron required up to 8 t of charcoal (which, in turn, required 4 t of wood), and up to 2.4 t, or 90 MJ, of wood were needed to make a kilogram of glass ([Smil 2016a](#); [Sieferle 2001](#); [Figure 4.1](#)). Compared to Europe (and even more so to deforested North China), the North American wood supply was extraordinarily high: in 1850 when the US mean reached about 95 GJ/capita, it was an order of magnitude higher than in Germany or France ([Schurr and Netschert 1960](#)).



fig. N.

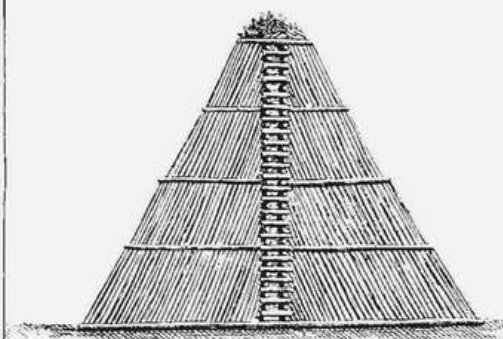


fig. L.

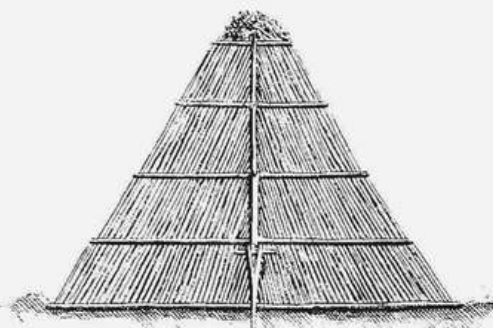
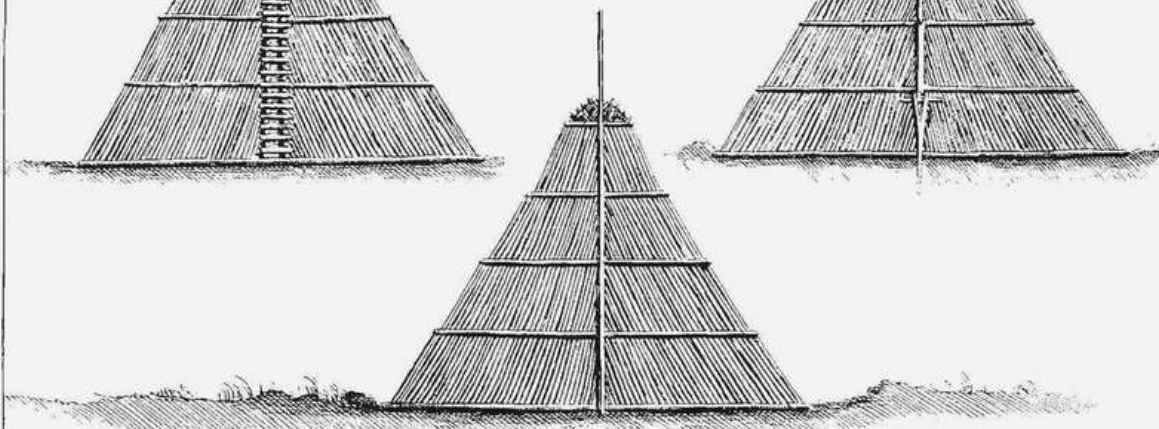


fig. M.



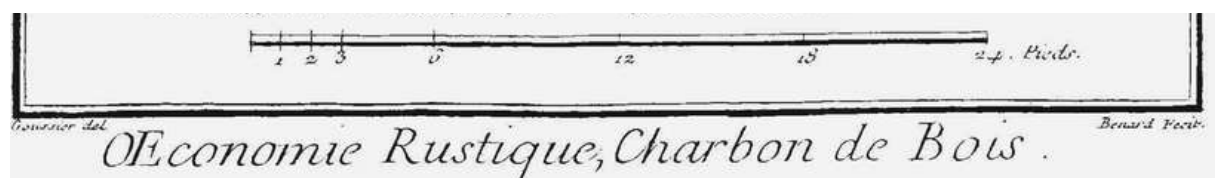


Figure 4.1 Stages of charcoal making pictured in *Encyclopédie, ou dictionnaire raisonné des sciences* (1751–1766), Avec Approbation et Privilège du Roy. Paris.

Coal was used in North China in antiquity to smelt iron ore, and locally for heating in Roman Britain and later in parts of medieval Europe. But its larger-scale extraction (mainly for metal working, soap making, brewing, and heating by poor families) began only in England during the 16th century and accelerated once new reverberating furnaces had started allowing high temperature suitable for glassmaking. Remarkably, all coalfields that made the United Kingdom the world's largest coal producer during the 18th and 19th centuries were already exploited before 1640 (Nef 1932; Flinn 1984). Output rose from 25,000 t in 1600 to 3 Mt in 1700 and about 13 Mt in 1800 (Pollard 1980) and coal began to supply more than half of the country's thermal energy no later than 1620, two-thirds by 1650, three-quarters by 1700, and 90% a century later (Warde 2007).

After converting the harvested mass of wood and extracted mass of coal to their energy equivalents (air-dry wood has 17 GJ/t, anthracite contains 30 GJ/t, good-quality bituminous steam coal has 25 GJ/t) we can trace the changing supply shares and even pinpoint the tipping points when coal began to supply more than half of all primary energy. Again, as with demographic transitions, there are many national peculiarities. In France, with a large territory and with most of its *départements* well forested, wood supplied more than 90% of primary energy in 1800, 75% by 1850, and less than 50% only by the mid-1870s (Barjot 1991). Swedish economy was predominantly wood based until the first decade of the 20th century (Energy History 2015). During the closing decades of the 18th century the newly formed United States had access to vast eastern forests but by the middle of the 19th century large areas of New England, particularly in Massachusetts, became deforested and the country could not have supported its expanding industries by relying on wood and charcoal (Foster and Aber 2004; Smil 2016a).

American coal extraction supplied 10% of all primary energy in 1851 and 20% in 1863, and it began to provide more of the nation's energy than wood

did in 1884 ([Schurr and Netschert 1960](#)). By 1900 coal's share was up to 66% and it peaked at 77% in 1910. The absolute peak was reached only in 2005 but coal's share of primary energy declined to just 16% by 1976. Partial recovery (due to coal's use in electricity generation) lifted the share to almost 23% by the year 2000 but then the rise of hydrocarbon extraction reduced the contribution to just 14% by 2019 ([USEIA 2019](#)).

Japan's coal output surpassed half of the total fuels supply already in 1901, and my reconstructions of Russian and Soviet energy balances indicate that at that time wood still provided at least 75–80% of Russia's primary energy and that its share of the overall supply dipped below 50% only during the early 1930s, half a century later than in the United States ([Smil 2017b](#)). China remained almost totally dependent on wood during the first half of the 20th century and its share was still 98% in 1949 when the Communists took control. The nationwide tipping point came during the mid-1960s but for rural households, dependent on wood and straw, it was delayed until 1988 ([Zheng 1998](#); [Fridley et al. 2008](#)).

Wood-to-coal transitions can be traced by comparing times elapsed before coal began to supply 5% of a country's overall energy supply (the share signifying a takeoff point of large-scale coal extraction) and the year when it began to provide more than half of energy ([Smil 2017b](#)). In France it took 75 years (1800–1875), in Sweden 55 (1855–1910), in Russia/USSR about 50 (1885–1935), in the United States 41 years (1843–1884), in Japan just 31 (1870–1901), and in China a mere 14 or 15 years (1950/1951–1965). Again, excepting the United Kingdom, all of today's affluent economies were in advanced stages of transition by the end of the 19th century and reached the tipping points in periods shorter than today's average lifespan. Again, the advantage of late starters is obvious.

Dating of the tipping points makes it obvious that a commonly repeated label of the 19th century as the era of coal is wrong. My (inevitably approximate) integration of global consumption estimates for the 19th century confirms it as the last period of the millennia-long wooden age, with biomass fuels surpassing the worldwide combustion of coal nearly fivefold ([Smil 2008b](#)). Although coal's share in global primary energy supply stopped rising already before World War II the fuel was the dominant source of energy during the first half of the 20th century.

Transition from wood to coal made it possible to shift from proto-industrialization, based on small-scale smelting of metals and on artisanal

manufacturing, to full-scale industrialization. Ironmaking is a key example illustrating how it would have been impossible to energize industrial economies by wood ([Smil 2016a](#)). For millennia its production relied on charcoal, with improving efficiencies. Even if a metric ton of charcoal required just 3.5 t of wood and even if the smelting used only 0.7 tons of charcoal per kg of hot metal as do modern Brazilian charcoal-fueled blast furnaces ([Smil 2017b](#)), the world producing 1.25 Gt of pig iron (2018 total) by relying on charcoal would need about 3 Gt of wood, or about 4.7 billion m³. For comparison, the global harvest of all industrial roundwood to be used as sawn wood (mainly construction lumber) or wood-based panels (mainly plywood) and to produce pulp and paper was 1.8 billion m³ in 2016 ([FAO 2018a](#)), or less than 40% of the total that would be needed just to smelt iron ore. And if that wood was to be grown in tropical plantations of high-yielding species their area would easily surpass half of the Amazon Basin. Obviously, the output of modern wood-based ferrous metallurgy would have to be restricted.

Four other markets that drove the fuel's early expansion—household heating, industrial heat and hot water, railways, and ocean transportation—had eventually converted to cheaper and more convenient fossil fuels. Once the transition to hydrocarbons had gotten under way, coal's retreat was very rapid and in several countries, including the United Kingdom, the process had run its complete course. British coal output peaked in 1913 at 287 Mt, remained high until the 1950s, but was then displaced by the North Sea hydrocarbons ([Hicks and Allen 1999](#)). Coal output fell to less than 20 Mt by the year 2000 and the last British deep mine in North Yorkshire was shut down in December 2015, ending more than half a millennium of the country's coal industry ([Moss 2015](#); [Figure 4.2](#)). And there has been no coal extraction in the Netherlands since 1974 and in France since 2004.

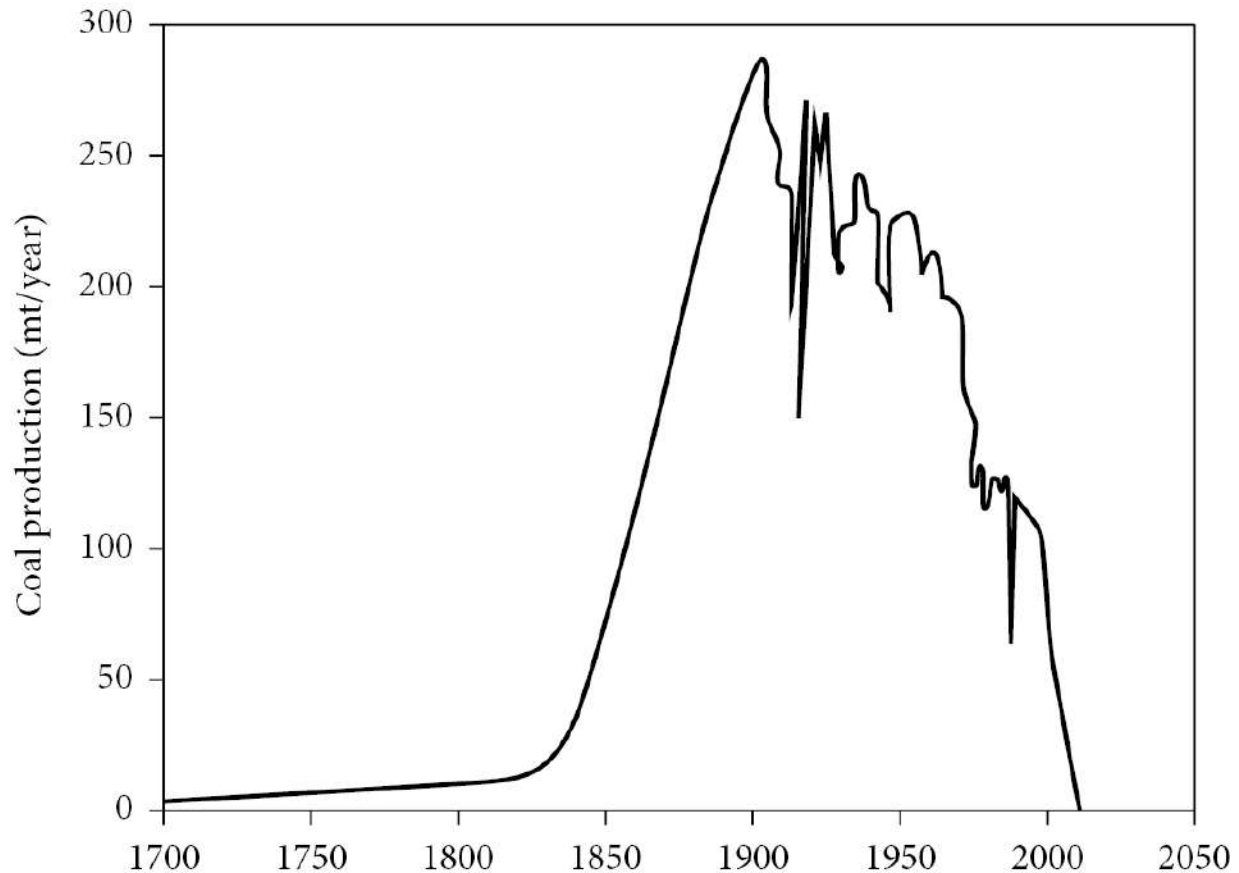


Figure 4.2 Complete trajectory of British coal extraction, 1700–2015. Plotted from data in DECC (2015).

In contrast, phytomass has never disappeared from national energy balances of affluent nations: there are no draft horses, no steam locomotives, no water wheels—but phytomass was never eliminated in any major economy. In 2017 about 2% of total US annual energy consumption came from wood and from industrial wood waste (bark, sawdust, chips, paper-mill residues) and the share for residential consumption (about 11% of all households burn cord wood or wood pellets) was also about 2% ([USEIA 2019](#)). And in 2016 EU countries derived about 6% of their primary energy from wood and wood products (mostly from pellets), with the share as high as 24% in Finland ([Eurostat 2019](#)).

The initial rise of coal was led by three major final uses: as the dominant fuel for industries, for households, and for energizing steam engines. After 1882 increasing shares of the fuel went to electricity generation and this conversion had more than made up for the three initial markets, which were eventually either totally eliminated (steam engines, household heating) or

greatly reduced (industries turning to liquid fuels and natural gas). Metallurgical coal to make coke for blast furnaces was another expanding market but once the affluent countries had begun to produce more steel by recycling scrap metal, that demand declined in the West. Enormous steel requirements in Asia, however, have made China and India the world's largest operators of blast furnaces.

Rise of hydrocarbons

In global terms, coal kept its primacy during the first half of the 20th century and, surprisingly, my integration of global consumption data shows that even for the entire 20th century it delivered slightly more energy than crude oil—or (given the uncertainties of mass-to-energy conversions) that it was at least as important as liquid hydrocarbons ([Smil 2008b](#)). But the shares of the two kinds of fuel had shifted rapidly during the second half of the 20th century when crude oil supplied about 30% more of primary energy than coal and did so in a qualitatively superior manner.

Bituminous coal contains 22–25 GJ/t and brown coals (lignites) have less than 20 GJ/t (the poorest one even less than 10 GJ/t), while energy densities of crude oils and refined fuels derived from them cluster tightly around 42 GJ/t, roughly 75% higher value than that of steam coal. Crude oil's higher energy density means that a cubic meter of bituminous coal weighs 850 kg and contains around 20 GJ, while the numbers for crude oil (in a tank) are mostly around 900 kg and nearly 38 GJ. This difference determines the portability of fuels and hence their use for mobile applications. Coal-powered cars are possible, and test models were built and not just by tinkering enthusiasts. In the early 1980s GM introduced two turbine-powered cars using powdered coal, the converted Cadillac Eldorado and the Oldsmobile Delta 88 ([Tracy 2017](#)), but they were never commercialized. And a coal-fired intercontinental airplane is impossible. Liquid fuels are also much easier, and much cheaper, to transport over long distances by large tankers or by pipelines, and can be stored inexpensively in above-ground tanks as well as in underground spaces without deterioration in quality.

Refining of crude oil produces liquid fuels for a wide range of final uses, from the lightest products used for passenger cars (gasoline) and flying (kerosene), to heavier diesel oil (used by heavy road and off-road

machinery, locomotives, and shipping) and the heaviest residual oils used in heating and by ocean-going vessels. Moreover, naphtha (the fraction between gasoline and kerosene) is a major feedstock for petrochemical industry, and the heaviest fractions provide lubricants and paving materials (asphalt). The specific density of natural gas (actually a mixture of gases dominated by methane) is only 1/1,000 that of crude oil but the gas is readily compressed and transported in large-diameter pipelines. Unless compressed or liquefied, however, it is unsuitable for mobile applications and its long-distance transport by tankers must take place in a liquefied form. The heavier gases usually present in the mixture (ethane, propane, and butane) are outstanding petrochemical feedstocks ([Smil 2015a](#)).

Commercial crude-oil extraction began in Russia, Canada, and the United States during the 1850s, with kerosene as the main refined product. Early development was restricted by the lack of suitable pipelines, inadequate refining capabilities, and the absence of markets for heavier fuel fractions. Large-scale production of automobiles (starting in 1908) created new demand for gasoline, but before World War I only Russia derived a large share of its primary energy from crude oil. In the United States crude oil accounted for nearly 30% of all commercial energies during the late 1930s and by 1950 it surpassed 50%. The rest of the world began to rely on crude oil only after World War II, thanks to inexpensive Middle Eastern exports. The first important find in the region was made in 1908 in Iran; discoveries of most of the giant Middle Eastern fields came between the late 1920s and the early 1960s, with the world's largest one, Saudi al-Ghawār, drilled in 1948 ([Li 2011](#)). Large-scale exports of crude oil necessitated the development of large tankers during the 1950s and 1960s.

In 1950 crude oil provided less than half of energy supplied by coal; by 1960 its shipments were equal to more than 70% of worldwide coal consumption, and the tipping point, when oil began supplying globally more energy than coal, came, according to the UN statistics, in 1967 ([UN 1976](#)). But because of uncertainties in both output totals and conversion rates of coal, the tipping point could have been reached already in 1963 or 1964 ([Figure 4.3](#)). In 1973 and 1974 oil reached the relative peak, as it supplied about 48% of the world's primary commercial energy, or no more than half of coal's peak share reached in the early years of the 20th century (again, when we count only commercial energies).

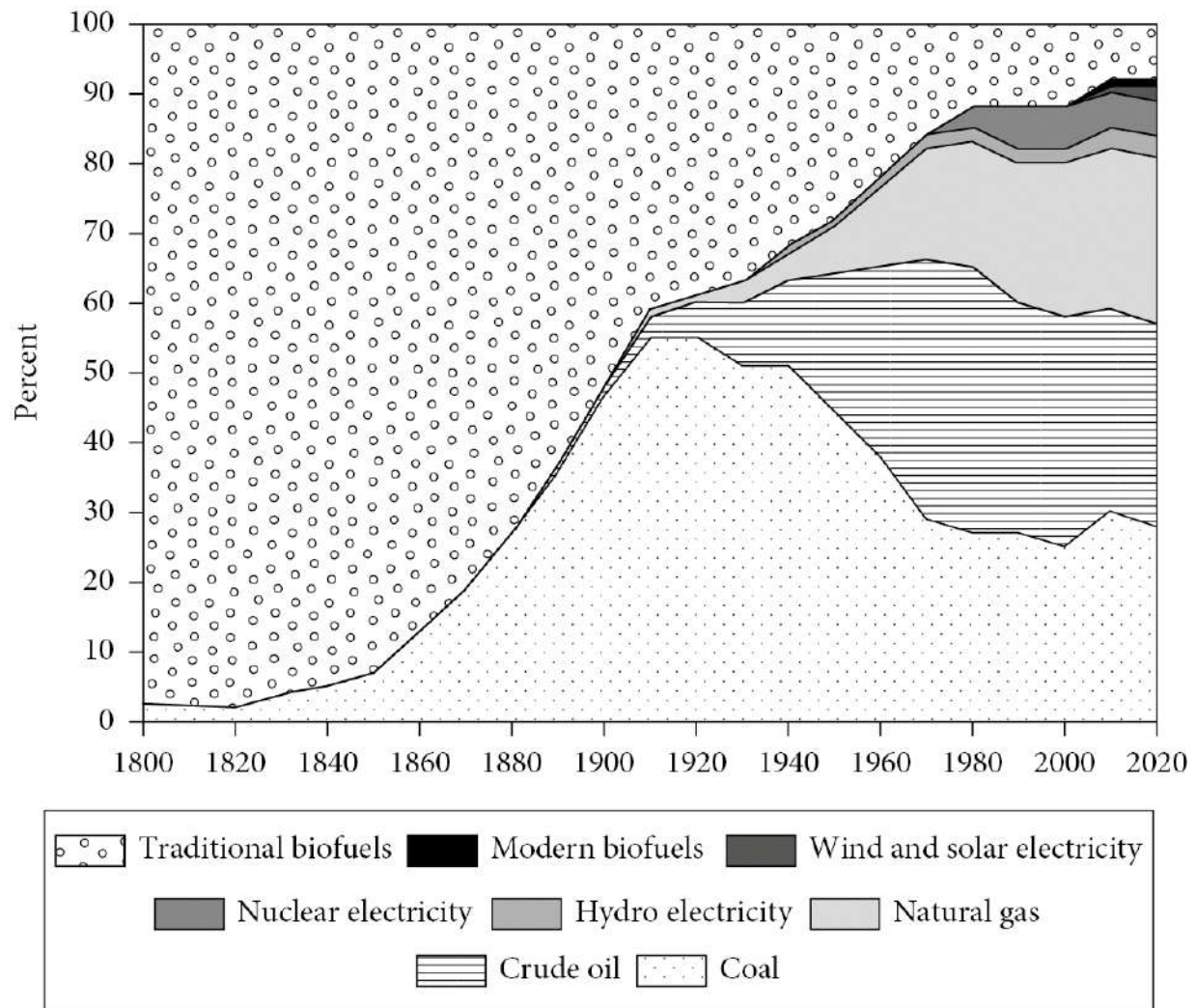


Figure 4.3 Global energy transitions, 1800–2015. Based on [Smil \(2017b\)](#).

In the wake of the OPEC-driven quintupling of oil prices in 1973 and 1974 and their further nearly quadrupling in 1979–1980, the retreat from this peak was both rapid and substantial. There was a slight decline in absolute consumption in 1975 but then a new demand peak that was reached in 1978 was not surpassed until 1988. By 2010 subsequent steady growth of oil demand resulted in absolute consumption nearly 50% higher than in 1973—but, concurrently, oil's share kept falling to less than 39% by 1990 and (due to the enormous rise of China's coal output) it was only about 33% by 2019.

Consequently, it is most unlikely that oil will ever regain its past peak share of 48% of the world's primary energy. Rising shares of renewable (wind and solar) electricity generation have received widespread media

attention but they have not been the main reason for checking oil's relative growth. That reason has been overwhelmingly due to the emergence of natural gas as a truly global fuel ([Smil 2015a](#)). Its steadily expanding post-1950 extraction and extensive pipeline construction—first in North America, later in Europe to export the Dutch and the North Sea gas and to bring the Siberian gas to Western Europe—resulted in slowly rising shares, from 17% (of commercial energies) in 1970 to 22% by the year 2000 and to just over 24% in 2019 ([BP 2020](#)).

Further gains will be driven by liquefied natural gas (LNG). The fuel, traded since the 1960s through a limited number of long-term contracts, has become a truly global fuel because of intercontinental shipments made possible on one hand by the rising capacities of LNG tankers and on the other by the diffusion of small-scale liquefaction facilities and floating LNG platforms. By 2019 about 49% of all exported natural gas trade was handled by LNG tankers, as more than 20 countries sold and more than 30 countries imported the fuel. Energy density of natural gas is only about 1/1,000 of liquid fuels' value, averaging 33–38 MJ/m³ compared to 35–36 GJ/m³ for major liquid fuels. This value precludes any use of (uncompressed) gas in flying, even in land transportation—but it is no obstacle to the fuel's stationary use, as it can be delivered inexpensively and reliably through long-lasting pipelines.

Coal transformed both productive activities and transportation as it energized unprecedented economic globalization, while the transition from coal to hydrocarbons was above all a shift toward higher efficiency, greater convenience, and reduced environmental impact. Making glass, pasteurizing food, or heating hospitals can be done perfectly well by either the combustion of coal or natural gas—but in the latter case there are obvious advantages of higher combustion efficiency, greater ease of operation, improved comfort, and reduced pollution.

The switch from coal to natural gas was particularly welcome in space heating. Winter operation of inefficient (less than 40%) coal stoves required seasonal coal storage (in basements or in sheds), carrying of coal pails to individual rooms, and repeated lighting and stoking of stoves and ash removal. Moreover, it entailed non-negligible fire hazard and the risk of CO poisoning. In contrast, the latest natural-gas-fired furnaces are more than 95% efficient, they are supplied by distribution pipelines, their operation requires nothing more than setting a thermostat (and an annual checkup),

and only water and CO₂ are generated on site. In the United States the transition from coal stoves (and also from oil-burning furnaces) was largely accomplished during the 1970s, in most European countries a decade or so later.

Coal-fired locomotives and steamships enabled rapidly expanding networks of railroads and mass-scale intercontinental travel. Between 1825 and 1900 the total length of British railways grew from just 25 km to 30,000 km, and the global aggregate reached 775,000 km (Williams 2006; Mitchell 2007). An excellent illustration of new steamship capacities is provided by decadal totals of the trans-Atlantic immigration from Europe to the United States: during the 1840s it was 1.37 million people; during the first decade of the 20th century it was 13.7 million (Bandiera et al. 2010). Impacts of coal-driven transportation revolutions were dwarfed by the transition from coal to liquids and, even more so, by the emergence of new engines burning gasoline and kerosene. Adoption of diesel engines in shipping displaced solid fuels in waterborne transportation of all bulk materials and finished products and the unprecedented integration of the world's economies could never happen without massive diesel engines with capacities of up to 90 MW: they have been the indispensable prime movers of globalization (Smil 2010a).

The magnitude of this transition is perhaps best appreciated by charting the trajectory of container-ship capacities since 1956, when the first vessel designed to carry stacked steel boxes could carry an equivalent of 100 TEU (20-foot equivalent units). A decade later the largest ship capacity was up to 1,300 TEU, by 1996 it reached 6,000 TEU, and by 2019 MSC (the Mediterranean Shipping Company) introduced the Gülsün class of container ships capable of carrying 23,756 TEU (Smil 2010a; MSC 2019). Worldwide container port traffic was less than 10 million TEU during the 1970s; it reached 225 million TEU in the year 2000, and nearly 793 million TEU in 2018 (World Bank 2019).

On land, the transition from coal to diesel oil (and electricity) resulted in the elimination of steam locomotives, as more powerful diesel (or electric) locomotives were able to pull trains of more than 150 cars, often with double-decker containers. In the West this transition was completed during the 1960s, in China only during the 1980s. But in terms of overall economic impact no other modern development was as consequential as the invention and gradual diffusion of gasoline-fueled internal combustion engines.

Technical milestones will be noted in the next section; here I will review the diffusion of car ownership and consequences for crude oil consumption.

During the 1860s, the first decade of the modern oil industry, the most important refined product was kerosene for lighting (replacing whale oil) and lubricants; waxes and asphalt were useful non-energy byproducts. By 1880 kerosene was 75% of the total output of US refineries, gasoline just 10% (USBC 1975). After 1882 electricity began to displace kerosene in urban lighting, but by 1908, when Ford Motor Company introduced its mass-produced and affordable Model T, US kerosene output was still three times that of gasoline. The subsequent growth in American car ownership was quite rapid. Annual sales rose from 180,000 in 1910 and 1.5 million in 1916, registrations of all motor vehicles went from more than 1 million in 1913 to more than 10 million in 1921, and by 1929 nearly half of all households owned a vehicle (USBC 1975).

As a result, kerosene and gasoline shares began to move rapidly apart and two new markets for kerosene (for cooking stoves and portable heaters) could not prevent the fuel's slide into marginality. In order to derive higher share of gasoline from an average barrel of crude oil, refiners introduced thermal cracking and, starting in 1923, more effective catalytic cracking followed by further improvements. These treatments have raised the US refinery yield of finished gasoline to 45–47% of the total output volume (USEIA 2018a). Diffusion of American car ownership stagnated during the economic crisis of the 1930s and the 50% mark was reached only once the production of passenger cars had resumed after World War II. Four out of five households had a car by 1960 and the rate had saturated at about 90% by the early 1990s, while home ownership rate has remained below 70%. Rapid automobilization began in Western Europe in the late 1950s, in Japan starting in the 1960s: between that year and 1972 Japan's gasoline demand had quadrupled.

Demand during the closing decades of the 20th century was kept up by households acquiring multiple cars. In 1960 about 57% of American households had just one vehicle, and 2.5% had three or more; by 2016 the respective shares were 33% and 21%, and a similar trend has been seen among higher-income families in Europe (Berri 2009; Governing 2018). Nationwide mean in the United States is now almost exactly two vehicles (1.97 in 2016) per household, with the highest rates (around 2.25) in several smaller Californian cities, and the highest numbers of vehicles in

households whose head is 45–55 years old ([Berri 2009](#)). After the near-saturation of Western and Japanese markets, the next big shift in global car ownership came with China's precipitous motorization.

In 2000, two decades after the start of Deng Xiaoping's economic reforms, China produced just 607,000 cars but the total reached nearly 26 million vehicles in 2019 (OICA 2019). Chinese expansion helped to put the global number of all road vehicles above 1 billion in 2010 and the aggregate reached 1.28 billion by 2015, with passenger cars accounting for 80% of the total and with Europe having nearly 390 million and the United States 264 million vehicles (OICA 2018). A recent survey shows cars in 88% of American households with other shares ranging from 85% in Germany to 47% in Brazil, 17% in China, and 6% in India ([Poushter 2015](#)). These trends mean that the global peak of gasoline demand is not imminent, although its arrival could be accelerated by rising sales of electric vehicles.

Kerosene made a strong post-1960 comeback as the superior aviation fuel for gas turbines (jet engines), new prime movers deployed after World War II (propeller planes were powered by gasoline). Kerosene has about 13% higher specific density than aviation gasoline but only a marginally lower (less than 1%) energy content; hence jetliners can fly at least 10% farther with the same volume of kerosene. Moreover, kerosene is also cheaper, has lower evaporation losses, and has lower risk of ignition. Global data for total passenger-kilometers (pkm) are the single best indicator to capture the expansion of flying. During the propeller era the annual total rose from 96 million pkm in 1929 to 28 billion pkm by 1950, but the total reached 2.8 trillion pkm in 2000 and 6.6 trillion pkm by 2015, and the pre-COVID-19 forecasts expected further substantial increases during the 2020s and beyond (ICAO 2018; [Figure 4.4](#)).

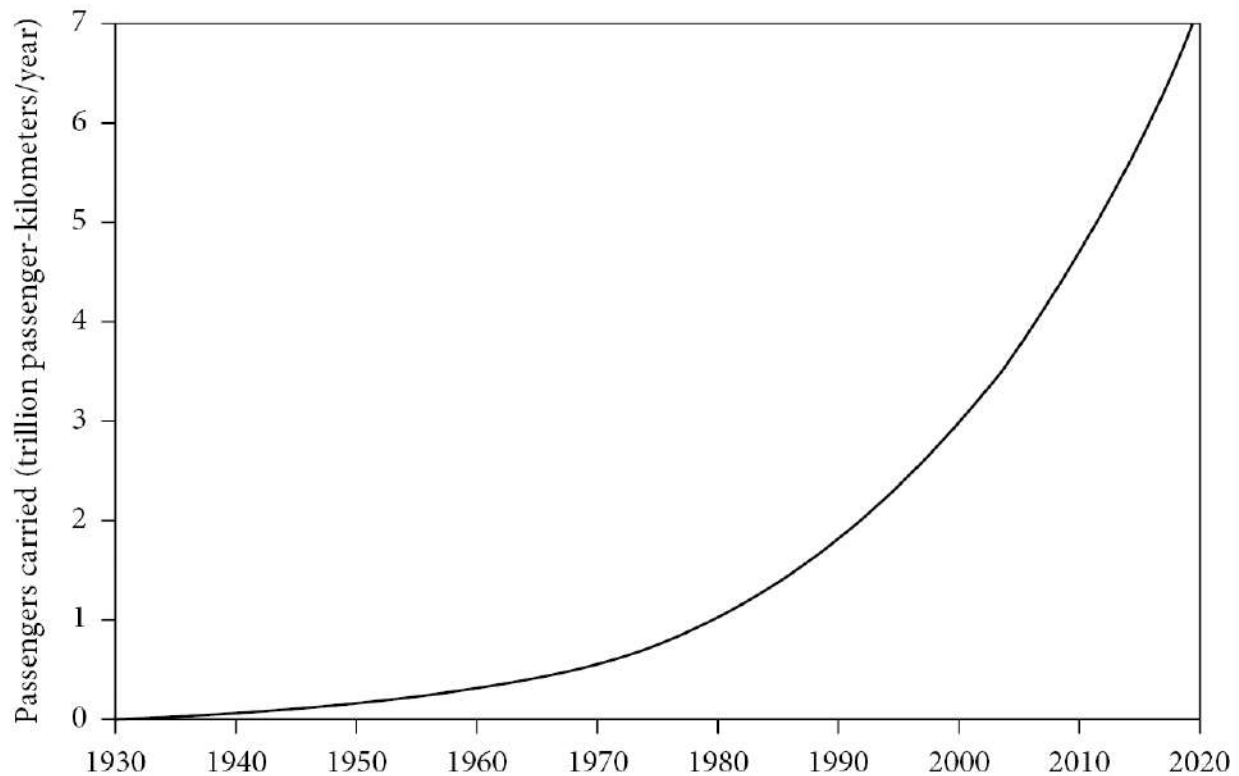


Figure 4.4 Growth of global commercial aviation (in passenger-kilometers), 1930–2020. IATA (International Air Transport Association) forecast is for further strong growth, with 8.2 billion passengers carried by 2037 compared to 4 billion transported in 2017.

Prime movers: From animate to inanimate power

Studies of energy transition focus on fuels but that is an incomplete perspective, as the epochal shift to fossil fuels was largely driven by the invention and diffusion of new prime movers. Human muscles were the only prime movers (sources of mechanical energy) before the domestication of animals. Continuous work by healthy adults could proceed at power rates ranging from 50–70 W for women to 80–100 W for men. Child labor, common in all premodern societies, could provide 30–50 W. Brief exertions could deliver several hundred watts, and massed labor was obviously required to move heavy stones for ancient construction projects ranging from megalithic structures of the Atlantic Europe to the building of Giza's three large pyramids. Twenty men pulling a wooden sled with a massive stone could briefly work at aggregate rates of 8–12 kW ([Smil 2017a](#)).

Domestication of animals multiplied kinetic energies under human control. There were three distinct uses: harnessed draft animals used for

fieldwork and for road transport; pack animals (horses, donkeys, camels, yaks) used to carry loads; and animals for riding (horses, donkeys, camels). Their performance depended on their species, size, age, experience, and proper feeding, and, as with people, there were large differences between the power of brief exertions and sustained work ([Smil 1994](#)). Sustained power was just 100–150 W for donkeys and 200–400 W for cattle and water buffaloes, and most horses delivered 500–700 W, less than one horsepower (745 W). Two-horse teams produced 1–1.5 kW of steady exertion, and large teams of horses (14–32 animals) used to pull America's first grain combines during the 1890s had aggregate power of 8–20 kW.

The relationship between human and horse power was well appreciated during the 18th century, when a good horse's work was equal to that of seven men but a typical ox replaced only 2.5 adult males. Using these equivalents, [Dupin \(1827\)](#) calculated that during the early 19th century French farmers had roughly quintupled the power of their labor force by deploying draft animals, while British farming, with larger numbers of better-fed animals, multiplied its labor force 12 times. The same conversion ratio for US farming in 1920, when the total of working horses and mules peaked at nearly 21 million, indicates that American farmers had multiplied their labor potential more than 15-fold.

Transition to fully mechanized field farming began slowly with the first gasoline-fueled tractors made in the United States between 1889 and 1892, but by 1920 only 3.6% of all farms had at least one tractor, while 90% had horses or mules ([Williams 1982](#); [Olmstead and Rhode 2001](#)). Subsequent mechanization was rapid: by 1933 draft animals and tractors had the same potential power and the 1930s also saw the shift from gasoline- to diesel-powered machines. By 1950 tractors accounted for 88% of the total and the transition was essentially complete in 1960, when animal power was mere 3% of the total. Land previously used to produce animal feed could be planted to food or industrial crops, a shift that increased effective cropland by about 30%. In 1910, before the expansion took off, working animals had aggregate potential power of about 14.5 GW; by 1960 the total power of agricultural machinery was nearly 65 GW. This mechanization reduced the need for rural workforce by 1.7 million, accounting for more than a quarter of all farm employment decline between 1910 and 1960 ([Olmstead and Rhode 2001](#)).

Most of Europe began the transition to tractor-powered farming only after WWII, and in some countries (Poland, Romania) horses were used well into the 1980s. China began to introduce small, hand-guided tractors in rice fields during the late 1950s, but the mechanization of the country's farming took off only during the 1980s, and sub-Saharan Africa (except for the Republic of South Africa) is the only major region where the transition to inanimate prime movers in farming is still in its earliest stage. At the beginning of the 21st century roughly 500 million working animals still provided about a fifth of all mechanical power in agriculture ([Smil 2017a](#)).

Waterwheels, the first inanimate prime movers that helped us to ease and to speed up such previously laborious and tedious tasks as milling grain, pressing oilseeds, crushing ores, or sawing timber, had already been introduced during antiquity. They were in relatively common use during the late Roman Empire and became even more widespread throughout medieval Europe as well as in parts of the Middle East and East Asia ([Smil 2017a](#)). Even during the 18th century European wheels had typical capacities of just 3–5 kW. Only the 19th century saw many large, and much more efficient, metal wheels with capacities up to 50 kW, but they were soon displaced by water turbines. In many places these machines, rather than the steam engines, were the leading prime movers of industrialization, and after 1882 the transition to water turbines had resulted in multiplying commonly installed unit capacities by four to five orders of magnitude.

Windmills began to spread only about a millennium after the introduction of small horizontal waterwheels ([Holt 1988](#)). Medieval tower windmills were heavy, inefficient, low-power wooden machines, but later designs became instrumental in draining Holland's low-lying lands and powering the country's proto-industrialization during its Golden Age ([Unger 1984](#)). In Western Europe, as well as in the United States, windmills reached their apogee during the latter half of the 19th century. The windmill era ended with the availability of affordable electricity, and the new age of wind power started only during the 1980s (in California) and, thanks to better subsequent designs (three large plastic blades mounted on tall steel towers), wind generation now dominates the contributions of new renewables.

The earliest steam engines of the early 18th century were so inefficient that they could operate profitably only at coal mines. Only after Watt's 1776 patent had expired did it become possible to develop new high-pressure designs suitable for mobile applications ([Rosen 2010](#)). Britain was, once

again, in the lead, with the first railway between Darlington and Stockton in operation by 1829, but subsequent expansion was also rapid in major continental economies and in the United States. Horse-drawn transportation was still needed to move people and to distribute goods within cities and in places not served by expanding railway networks. The first development to change that was the adoption of electric street cars. Contrary to what some historically inaccurate studies have concluded ([Cherif et al. 2017](#)), horses as urban prime movers were not displaced by internal combustion engines (that is, by passenger cars and buses) but by electric motors (electric streetcars). Most urban horses were kept not as private animals but to pull horse-drawn omnibuses (first in New York in 1827) and streetcars (first in London in 1831).

The first electric streetcar line was completed in May 1881 in Lichterfelde, Berlin's southern suburb, by Werner Siemens, and many European cities introduced their lines shortly afterwards ([Figure 4.5](#)). Short American lines followed in 1886 (Montgomery, Alabama and Scranton, Pennsylvania), 1887 (Omaha), and 1888 (Richmond, Virginia) ([Sullivan and Winkowski 1995](#)). Networks in large cities came during the 1890s, New York in 1890, Phoenix in 1893, and Boston in 1899. Additions during the first decade of the 20th century included Los Angeles in 1901 and San Diego in 1907. In many cities, streetcar lines were extended to urban fringes and became the first mechanical enablers of suburbanization. In terms of the total available power, the tipping points between horses and electric motors in public transportation were reached in most European and North American cities between 1895 and 1910 but horse-drawn streetcars remained on some routes until 1917 in New York and until 1923 in Pittsburgh ([Roess and Sansone 2013](#)).

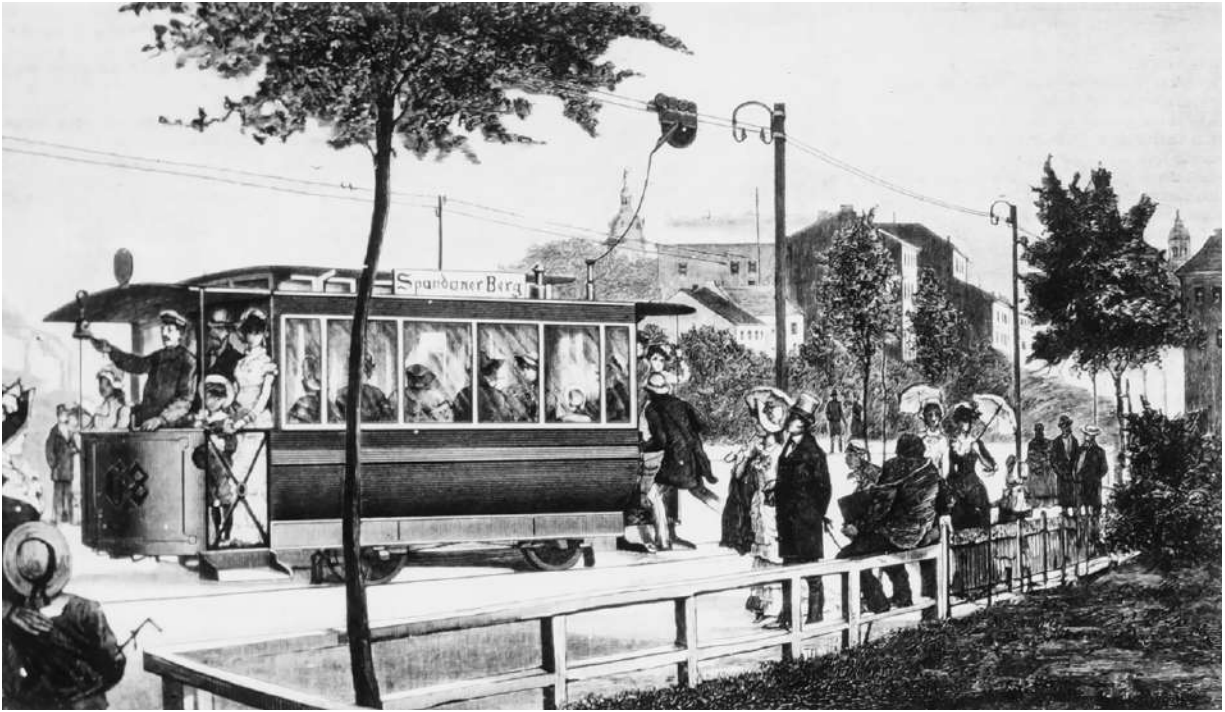


Figure 4.5 An electric streetcar in Frankfurt-am-Main used iron wires attached to telegraph poles. Image from *Scientific American*, August 16, 1882.

The second new prime mover whose origins date to the 1860s, the internal combustion engine, eventually eliminated any remaining urban draft animals: once small trucks had become available there was no need for cartage horses. Of course, the internal combustion engine found its greatest niche in passenger cars. The first two decades after the testing of pioneering models by Gottlieb Daimler and Wilhelm Maybach in 1886 and, independently, by Karl Benz, saw only their limited diffusion ([Walz and Niemann 1997](#)). Improving designs competed in newly popular races—the first one in July 1894 from Paris to Rouen (126 km), the next year Paris to Bordeaux, a round trip of nearly 1,200 km (Beaumont 1902)—but remained far too expensive.

That situation changed with the introduction of Ford's Model T in 1908, which went on sale on October 1, 1908 ([McCalley 1994](#)). Its engine could develop nearly 15 kW (about 20 hp), and design adjustments and manufacturing advances (most notably moving assembly lines) made the car widely affordable. When its production ended in 1927 the company delivered 15 million units. Concurrent development of trucks was accelerated once diesel engines (deployed for the first time in trucks in

Germany in 1924) had become the prime mover of choice for all heavy water and land transportation as well as all construction and off-road machinery ([Smil 2010a](#)).

Inherently more efficient diesels were too heavy for flight but gasoline engines had undergone a rapid evolution between 1904 (the first manned flight of a heavier-than-air plane by the Wright brothers) and 1944, when WWII fighter planes could reach speeds of nearly 800 km/h (the Supermarine Spitfire at 795 km/h). Higher speeds, and affordable intercontinental flight, became possible only thanks to gas turbines. Their first use in German, British, US, and Soviet jet fighters of the 1940s was followed by the first commercial jetliners of the 1950s and by further scaling up and the introduction of turbofans during the 1960s. In these engines most of the compressed air bypasses the engine's core and leaves the engine at about half the speed of the air that goes through the engine's combustor.

Since the 1960s gas turbines have also had a great commercial success as stationary prime movers providing the most efficient way to generate electricity, and combined-cycle machines (steam turbines attached to gas turbines to be powered by their hot exit gas) have efficiencies of more than 60%, performance unequaled by any other prime mover. But steam turbines still generate most of today's electricity. Invented in 1884 (by Charles A. Parsons), the largest units rated 1 MW by 1900 and 25 MW just before World War I ([Smil 2005](#)). After a period of stagnation, the post-WWII demand for electricity led to the maximum ratings of nearly 600 MW by 1960 and to 1,000 MW (1 GW) by 1965. Subsequently, typical sizes have remained below 1 GW but units installed in large nuclear stations reached records of 1.75 GW.

The tipping point for the transition from animate to inanimate energies was during the 1880s in the United States, early in the 20th century for the global average, and in the century's closing decades in many populous Asian countries. By 1900 steam engines and steam turbines claimed 60% of US mechanical power, draft animals just over a third, waterwheels and windmills less than 4%, and newly diffusing internal combustion engines less than 2% ([Daugherty 1928](#) and [1933](#)). By 1929, thanks to mass-scale ownership of automobiles, internal combustion engines took over with about 88%, steam turbines claimed about 10%, and animal power was reduced to only about 1%.

Calculating the shares of individual components before and after the transition on the global level can be done only approximately. My estimate is the global economy in 1850 had nearly half of all useful kinetic energy delivered by draft animals, about two-fifths by human muscles, and the remaining 10%–15% by three inanimate prime movers, a combination of long-serving waterwheels and windmills and new steam engines ([Smil 2017a](#)). Within 50 years inanimate prime movers were about to claim more than 50% of the total: by 1900 their power was close to half of all useful kinetic potential, while the contribution of draft animals was reduced to a third and that of human muscles to no more than 20%.

By 1950 the transition from animate to inanimate prime movers was largely complete as aggregate power of human and animal labor was dwarfed by the installed power of fuel- and water-powered machinery dominated by internal combustion engines in vehicles and (in distant second place) by steam and water turbines. Human muscles added up to no more than 5% and draft animals no more than 15% of all available power. And by the year 2000 the capacity of all animate power was reduced to only about 5% of the total, and because of the mass-ownership of increasingly powerful passenger cars (about 1.2 billion units in 2018) the global shares of installed prime mover capacity are now dominated by internal combustion engines.

Of course, because of different load (capacity) factors, the shares of prime mover capacities differ from the shares of actually deployed energies. Because of large seasonal fluctuations in demand for labor, the total number of hours worked annually by peasants was often less than the number of hours worked by early industrial workers (with 12-hour shifts, including Saturdays) and no more than for today's typical annual rates (equivalents of 200–225 days of 7–8 hours). Water buffaloes used in Asian rice cropping worked 130–140 days, and horses in northern Europe (where only single summer crops could be grown) put in only 60–80 days of fieldwork.

Expressing these capacity factors as shares of annual maxima gives us the low means of 15–20% for people and 5–15% for draft animals. In contrast, steam turbines in nuclear electricity-generating plants have capacity factors around 90% and those in coal or natural gas-fired plants 45–55%; water turbines typically work 35–55% of all time, and stationary steam engines in factories and steam locomotives average 30–50%. But internal combustion engines in passenger cars have very low capacity

factors: even in the United States, where the average distance driven per year is now nearly 22,000 km, the factor (assuming the mean speed of 60 km/h) is merely 4%.

Perhaps the best way to appreciate the outcomes of this energy transition is to compare typical or modal power ratings, power/mass ratios, efficiency, reliability, and durability. Animate prime movers are inherently limited by the size of their bodies, by their metabolic rates, and by their muscle efficiencies ([Smil 2008b](#)). Unit capacities rose from less than 100 W for hard-working adults to less than 500 W for most draft animals, and up to 700–800 W for large, well-fed horses. Combined human exertion in labor gangs could raise the typical maxima ten- to 50-fold (up to about 4 kW). Harnessing horses or mules in exceptionally large teams of 30–40 animals to pull early combines in California or in Washington's and Oregon's Palouse wheat region could deliver up to 25 kW.

Even small pre-1930 tractors had power of 10–15 kW; now the world's largest tractor maker (India's Mahindra) sells machines rated between about 19 and 78 kW; and Deere, the American leader, offers designs rated from 140 to 400 hp—that is, from roughly 100 to 300 kW. In agriculture, typical power controlled by a single person thus rose an order of magnitude (15-fold) before the transition to inanimate prime movers, from 80 W for a peasant hoeing a field to 1,200 W for a farmer plowing with a team of two good horses. The shift from animate to inanimate power entailed an order of magnitude rise right at the transition's very onset (from 1.2 kW for a horse team to 12 kW for a small tractor) and by now the typical gain has been two orders of magnitude, from 1.2 kW for a horse team to 100+ kW for commonly used tractors.

Interestingly, the reciprocal value of this gain corresponds well to the eventual reduction of agricultural labor force: as typically deployed power grew by two orders of magnitude the share of American labor force employed in crop farming was reduced by two orders of magnitude. In the United States the total farm employment was around 80% of all labor force during the early 19th century ([Lebergott 1966](#)). By 1960, when the transition to inanimate power was virtually complete, farm labor force was an order of magnitude smaller at 8.1%, and during the second decade of the 21st century (when the total employment in cropping, animal husbandry, and aquaculture was less than 1.5%) the share of labor employed in

growing field crops by using more powerful machinery fell by another order of magnitude to a fraction of one percent (BLS 2014).

Growth of prime-mover capacities has been far more impressive in both stationary industrial applications and in transportation. The most powerful traditional stationary prime movers were windmills, and those used to drain Dutch polders had capacity of 20–30 kW—that is, 10^4 W (Stockhuyzen 1963)—while large modern diesel-powered pumps can produce up to 10^6 W. Waterwheels powering large bellows deployed to blow air into blast furnaces had a gross capacity of 10^3 W (Figure 4.6), while modern compressors run by gas turbines have capacities up to 10^7 W. Multiples for road transportation have been about 30- to 50-fold from 2.5 kW for a four-in-hand (a vehicle pulled by four horses driven by a single coachman) to 100 (75–125) kW for a small passenger car. Steam engines powering mid-19th-century trains developed 300–600 kW, while modern diesel locomotives have a power of 3–5 MW.

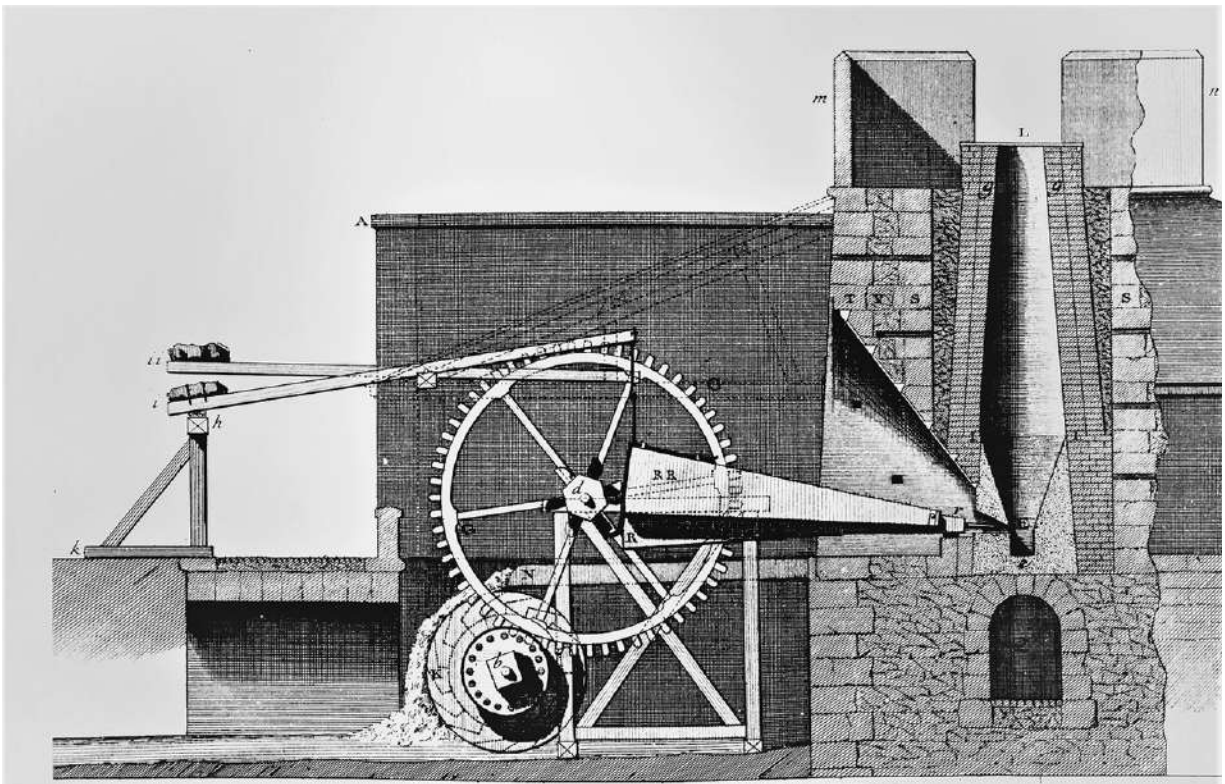


Figure 4.6 Late-18th-century blast furnace with bellows powered by an overshot waterwheel. From *Encyclopédie, ou dictionnaire raisonné des sciences* (1751–1766).

Power/mass ratios are the best indicators of portability and flexibility. Animate prime movers, be it manual laborers or draft animals, have inherently high ratios (the function of low efficiency of muscles) of around 1 W/kg, while the ratios for modern inanimate prime movers range from 15 W/kg for high-performance steam engines to 500 W/kg for modern internal combustion engines and more than 15,000 W/kg for turbofans. The difference of four orders of magnitude between the power/mass ratio of muscles and turbofans explains why all human attempts at muscle-powered flight ended in failure (often in death) and why Boeing 787 can fly between continents for more than 12 hours and carry some 300 people.

Besides being orders of magnitude more powerful, modern prime movers are also more efficient, more reliable, and more durable ([Smil 2008b](#)). Mammalian muscles convert chemical energy of food or feed to kinetic energy of useful work with efficiencies of no more than 15–20%. Large steam engines had rarely surpassed the higher rate and smaller machines powering steam locomotives had efficiencies of less than 10%. With efficiencies around 35% modern gasoline engines have approached the performance of small diesels (40%), whose largest designs (for marine vessels) just surpass 50%. And, as already noted, combined-cycle gas turbines have reached peak efficiencies of slightly above 60%. As for the reliability, gas turbines powering today's jetliners are expected to have a shutdown less than once for 100,000 operating hours (an equivalent of flying nonstop for nearly 11.5 years), and with regular overhauls they can last more than two decades.

Fundamental changes

Energy transition has brought four fundamental changes. First, it moved the global system away from the reliance on recently photosynthesized phytomass (aged just 3–5 months for crop residues, 3–15 years for shrubs and fast-growing trees, and mostly 10–80 years for mature trees) to fossil fuels (most crude oil deposits were formed 100–150 million years ago, many coal deposits older than 300 million years). Second, the transition had replaced fuels of low energy density (straw 15 GJ/t, air-dry wood about 17 GJ/t) by fuels of medium to high energy density, 22–25 GJ/t for bituminous coals, 42 GJ/t for crude oils.

Third, transition had replaced fuels that were difficult to store with fuels that can be stored conveniently and inexpensively. One cubic meter of chopped air-dry wood (15% moisture) stacked in a dry, sheltered place weighs just 300–450 kg and contains no more than 8 GJ, while the same volume of bituminous coal and crude will contain, respectively, 2.5 times (20 GJ) and nearly 5 times (38 GJ) as much energy. These differences also determine the portability of fuels and hence their use in transportation: wood-fired locomotion is possible but its steam engine would require frequent fuel resupply; wood-fired passenger cars capable of traveling 500 km on a single fuel charge are impossible; wood-fired intercontinental airplanes are unthinkable.

The fourth fundamental shift brought by energy transition has been the increase in power density of fuels measured per unit of the Earth's surface ([Smil 2015b](#); [Figure 4.7](#)). All phytomass fuels have inherently low power densities, producing annual harvests that are mostly well below 1 W/m^2 , with further substantial reduction when converting wood to charcoal (but, in a partial compensation, that fuel had nearly twice the energy density of air-dry wood). Consequently, running a modern high-energy civilization on phytomass would require enormous areas devoted to tree plantations.

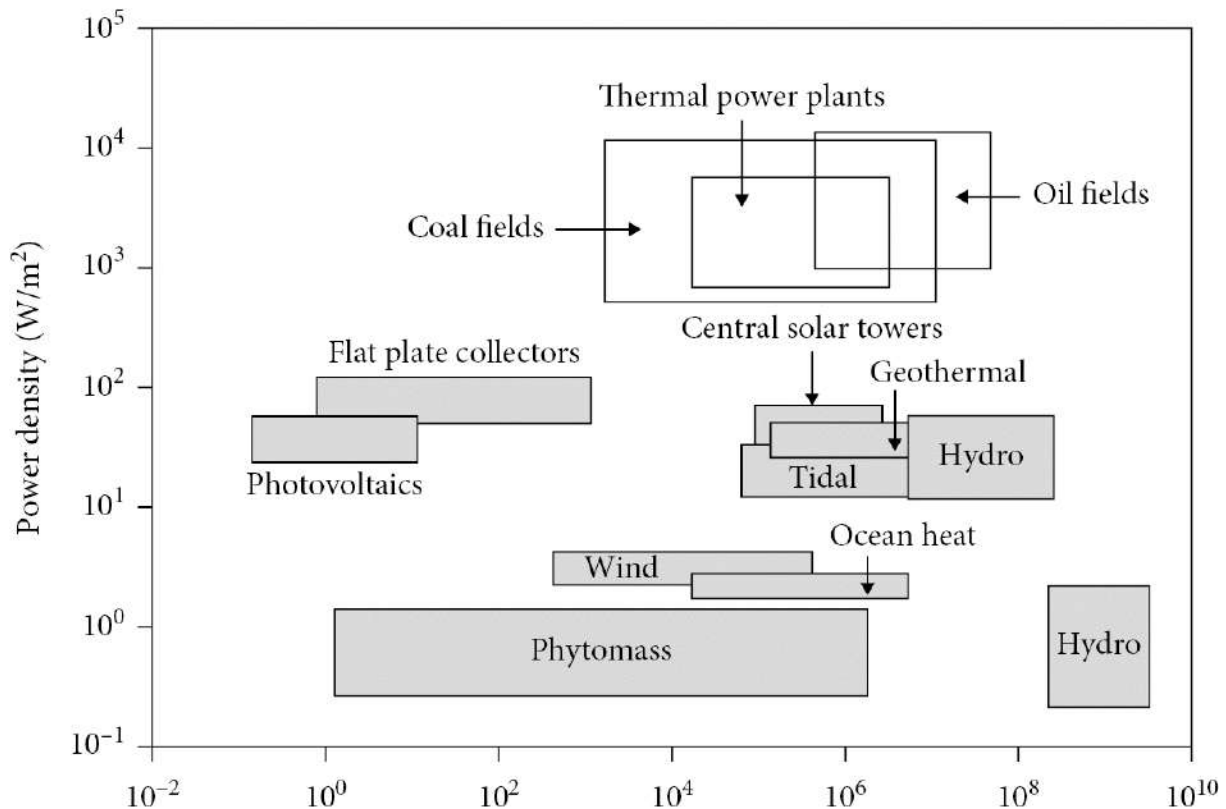


Figure 4.7 Power densities of renewable energies and of fossil-fuel extraction and conversion. Based on Smil (2015b).

In contrast, fossil fuels can be extracted in coal mines and hydrocarbon fields with densities of at least 10^1 W/m^2 but most commonly 10^2 – 10^3 W/m^2 and the most productive oil and gas fields can go an order of magnitude higher, concentrating production into relatively very small areas. Giant hydrocarbon fields have particularly high power densities. The adjective refers to their enormous resources (oil and gas in place), not to their spatial extent, as huge volumes of hydrocarbons are produced in a very concentrated way and transported by continental and intercontinental networks of pipelines and fleets of tankers.

Of course, these are finite, exhaustible resources but in many cases these giant fields have been producing copiously for decades; some have been in production (at declining rates) for more than a century. Eventually, their output will have to be replaced by a combination of new renewable sources of energy, including newly expanding wind and solar conversions that operate with low power densities, but highly efficient photovoltaic (PV)

cells may eventually surpass 50 W/m^2 . That our energy future will be even more electric comes as no surprise, given the post-1882 trajectory of energy transitions.

Electrification

The first fundamental electrical experiments and the first practical designs of electricity-powered devices came during the first half of the 19th century ([Smil 2005](#)). These electric milestones included the first battery (Alessandro Volta in 1800) and discoveries of the magnetic effect of electric currents (Hans Christian Ørsted in 1819) and of the induction of electric current in a moving magnetic field (Michael Faraday in 1831). Faraday's discovery eventually led to reorienting the emerging electric endeavors from limited options afforded by low-energy-density batteries to large-scale electricity generation in central stations. Thomas A. Edison had a key role in these epoch-making advances. His contributions ranged from a durable light bulb to a complete system of generation and distribution of electricity. His first plants, in London and New York, began to operate in 1882 and much larger enterprises followed soon ([Figure 4.8](#)).

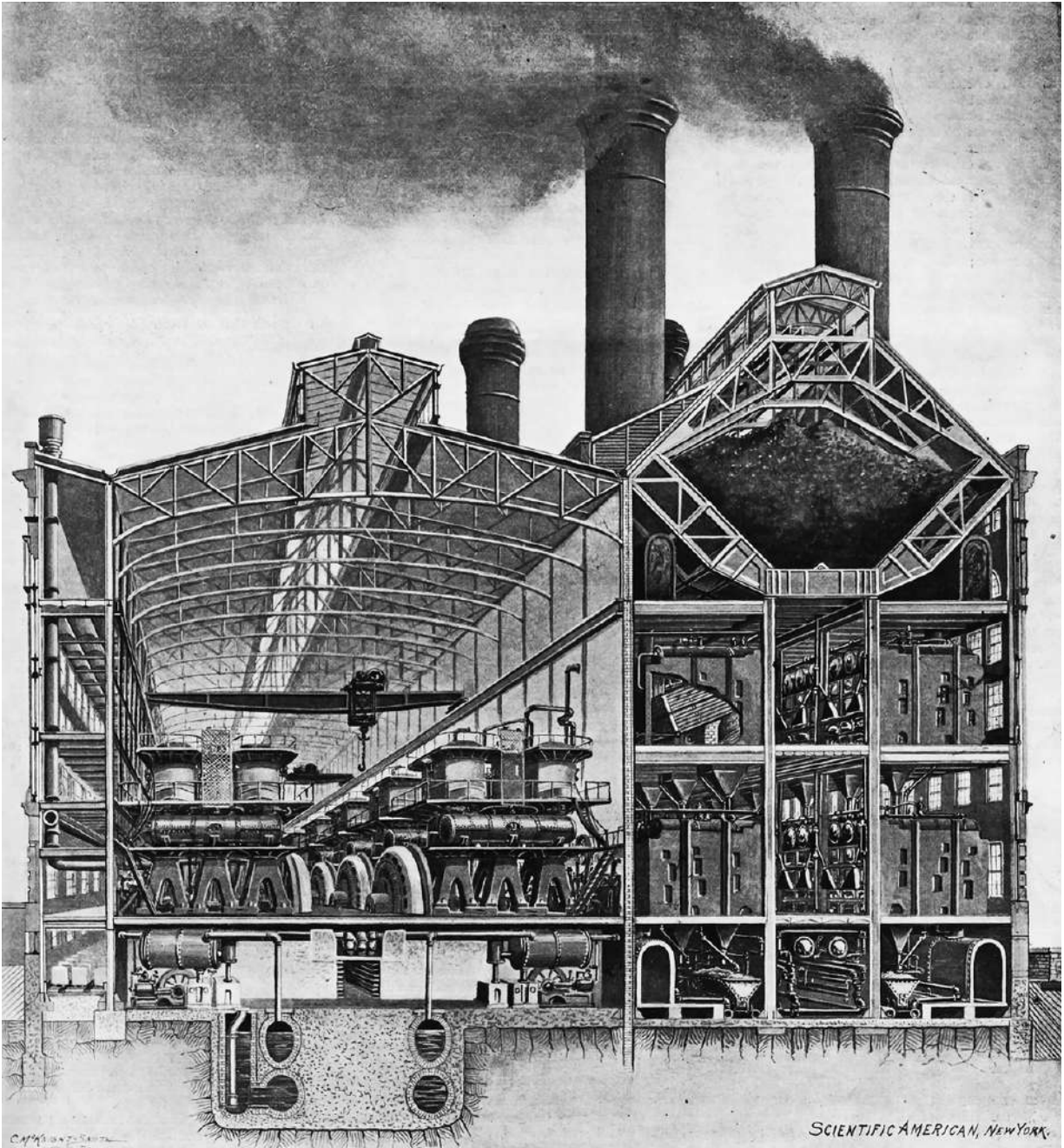


Figure 4.8 Edison's 93-MW electricity-generating station completed in New York in 1902, one of the last large stations using steam engines (inside the hall on the left part of the image; boilers are on the right). This image was the cover illustration of *Scientific American* for September 6, 1902.

During the next three decades electricity systems matured rapidly, and no list of key contributors to the rise of new electric age should leave out the names (alphabetically and limiting the total to a dozen entries) of Charles Curtis, Mikhail O. Dolivo-Dobrowolsky, Sebastian Z. Ferranti, Galileo

Ferraris, John D. Gibbs, Charles A. Parsons, William Siemens, William Stanley, Charles Steinmetz, Joseph Wilson Swan, Nikola Tesla, and George Westinghouse. Their enduring pre-1910 accomplishments remain the foundations of modern electric systems. Post-WWI development of these techniques resulted in much higher unit capacities, greatly improved efficiencies, and increased reliabilities. A short list of new inventions must include boilers burning pulverized coal (1920s); gas turbines (1930s); nuclear reactors for electricity generation (1950s); the first solar PV cells (1960s); increasingly powerful wind turbines; and widespread installations of wind turbines and more efficient PV cells since the beginning of the 21st century.

Global electricity generation is dominated by central fossil-fueled and hydroelectric plants; electricity is transmitted to individual users by underground cables or overhead wires; steam turbines are rotated by expanding pressurized steam in thermal stations; water turbines power large hydro stations; transformers step up or step down voltage before transmission or before specific use; and electric motors offer the most flexible, most affordable, and most reliable choice to energize countless industrial, household, and transportation tasks.

Electricity's importance

If the grand energy transition had been limited to displacing phytomass by fossil fuels we still would have more convenient and more efficient space heating, better sources of energy for many industrial processes, and faster ways of travel by using internal combustion engines and steam and gas turbines. But many modifications and a great deal of ingenuity would have been required to run a fossil-fuel-based society without electricity.

Starting a car engine is an obvious example of the inconveniences of a non-electric world ([Smil 2005](#)). All early gasoline-powered motor vehicles required starting by a hand crank, a task requiring a burst of muscle power and a risk of painful injury. Many better designs were tried (starting with acetylene, gasoline vapors, compressed air) but none of them could offer such a perfect solution as an electric starter introduced in 1911 by Charles Kettering. By the time the last Ford Model T was made in 1927 all new cars had electric starters. Much like the first cars, the first airplanes were started manually by propeller swinging but electric starters took over by 1930. Jet

engines (gas turbines) are now started by using compressed gas produced by an auxiliary power unit but that engine is itself started by a battery.

And starting engines would be only a small part of the enormous challenge of running the fossil-fueled world without electricity. For airplanes, think about the communication and navigation equipment, weather radar, cabin lights, climatization, and food and drink preparation (to say nothing about individual screens for in-flight entertainment). Cars could have windshield wipers and horns actuated by compressed gas, but to have non-electric lights for night driving and signaling would be a significant challenge, as would be automatic windows, adjustable side-view mirrors, and locks. Going back to manually operated windows or locks would be manageable; giving up all of the ubiquitous systems that depend on uninterrupted electricity supply would be another matter: no traffic lights, subways, high-speed trains, airports, hospitals, refrigeration, air conditioning.

And, obviously, no marvels of the new electronic world with instant communication and with the annual flow of information now at zettabyte (ZB, 10^{21}) level ([Seagate 2017](#)). Going back to mechanical computing would set us back many orders of magnitude in terms of performance while it would force us to rely on units whose mass (for an inferior performance) would be many orders of magnitude larger than today's desktops and laptops. Loss of electricity would be a radical cure to mobile phone addiction, but our health care would be profoundly compromised and life expectancies would decline. Most babies are now born in hospitals and the premature ones live for a time in incubators; vaccines must be refrigerated and so should all perishable food; the most revealing noninvasive diagnostic methods cannot work without electricity, nor can heart bypass machines or hemodialysis; many old people have their lives prolonged by being attached for a time to respirators and heart monitors.

Electrification of modern societies

Most of the world's electricity (about two-thirds in 2018) is generated by the combustion of fossil fuels, but right from its commercial beginnings in 1882 the industry has also used water, and then it added geothermal plants (1904), nuclear reactors (1956), and PV solar cells and modern wind turbines (starting during the 1980s). Electrification has thus been partially a

transition within a transition (from direct uses to an indirect exploitation of fossil fuels), and its fundamental utility, its eventual pervasiveness, and its omnipresent socioeconomic consequences have made it perhaps the most important of all transformative processes originating from technical innovations: “electric” might be the single most important adjective used to describe the functioning of modern societies.

Ubiquity of electric convertors reflects the unmatched qualities of this form of energy: its effortless availability and cleanliness at the point of use, its reliable delivery, and its affordability—for an average family in an affluent country monthly expense on electricity in 2016 amounted to only about 2% of disposable income ([Electric Choice 2018](#))—and flexibility (convertible to light or chemical transformation, heat or motion). No other form of energy has had such liberating impact on its consumers, as its adoption has eased, or eliminated, countless heavy and tiresome physical exertions, from manual threshing of grains to lifting irrigation water and from grinding grain to hand-washing clothes. Electricity has had an even more profound impact on extending the day, as all traditional forms of lighting were greatly inferior to its transformation in incandescent and fluorescent light bulbs, both now made obsolete by more efficient modes of lighting.

In tracing electrification’s progress I will concentrate on three universal transitions and their interrelated effects: on its abolition of darkness, a shift that in many parts of the world has now gone too far; on its consequences for the organization of factories and for industrial production; and on its transformation of household tasks and leisure activities, a shift that eased or eliminated many chores and left more time for leisure that, too, has become increasingly dependent on electricity.

Abolishing darkness is a truly magical technical advance, particularly because, one important exception aside, common ways of lighting at the very end of the pre-electricity era were not all that different from those of millennia ago. The exception, limited to major cities, was gas lighting made possible by gasification of coal and piped distribution of gas to buildings, first in London in 1812 and in subsequent decades in major urban areas in North America and Europe (New York in 1825, Saint Petersburg in 1839). Kerosene lamps, made possible by post-1860 crude-oil extraction and refining, had only the thin glass of their chimneys protecting their flame.

They were only a better version of traditional open-flame lamps and fire was an ever-present risk.

Light bulbs, sealed and screwed in place, represented an epochal departure ([Smil 2005](#)). US nationwide records of electrification begin in 1907, when only 8% of all dwelling units had electric service, all of them in cities. In 1912, when the US electric industry was 30 years old and when 16% of all dwellings were connected to the grid, a special issue of *The Annals of the American Academy of Political and Social Science* devoted to country life listed telephones and mail delivery as new rural conveniences but it made no mention of farm electrification ([Van Norman 1912](#)).

By 1920 the share of all dwellings with access to electricity rose to almost 35%, but farms were still at a mere 1.6%. A fundamental shift began only in 1936 with the creation of the Rural Electrification Administration, which provided for affordable loans and gave rise to numerous electric cooperatives ([Carmody 1939](#)). Subsequently, productivity increase averaged more than 40% in electrified farms and, remarkably, farming families were willing to give up 28% of their annual income in order to live in an electrified home and the benefits of rural electrification far exceeded its costs ([Lewis and Severnini 2014](#)).

Rural electrification programs pushed the US farm rate from about 10% in 1930 to nearly 33% in 1940; rapid postwar improvements raised it to 78% by 1950; and in 1956, the last year when this variable was monitored, 95.9% of farms and 99.2% of urban and rural non-farm dwellings were electrified. The process of electrification took 26 years (1882–1908) to connect 10% of all dwellings to the grid, 43 years to get to 50% (in 1925), 67 years to 90% (1953), and 75 years to 99%. Complete transition to electric lighting in the United States thus took about three-quarters of a century (1882 to 1956): that is, much longer than an average life span during the 1880s (at that time it was only about 45 years for males). Electrification in small European countries was accomplished before World War II, while in Canada and Australia it was completed roughly at the same time as in the United States. Japan was essentially electrified before World War II ([Kikkawa 2012](#)) and electrification is now virtually complete in China, while in India the rural share (at 77%) is still well below the urban rate of more than 98%.

In Africa urban and rural rates are, respectively, nearly 90% and less than 5% in Nigeria and about a third and less than 3% in Chad ([World Bank](#)

2019). Progress of rural electrification can be now measured by satellite observations available in the Nighttime Lights data set: they are surprisingly accurate even when analyzed at village level (Dugoua et al. 2018). In global terms electrification has a long way to go and the transition to electrified planet will not be completed even during the 2020s. In 2016 about 1.1 billion people had no access to electricity, down by 35% from 1.7 billion in the year 2000, and the forecast is for further decline to 674 million by 2030 (IEA 2017a).

Lights and motors

Lights have been the harbingers of electrification. One of the most remarkable realities is that the incandescent light bulb that started the process in the early 1880s was still the dominant electricity converter 75 years later, and that it retained this dominance during the remainder of the 20th century. The latest designs were much improved, compared to the first commercial light patented by Edison and Swan (Smil 2005). Original carbon filaments were replaced by metals a long time ago (first by osmium, then by tantalum, and since 1910 by tungsten) but their luminous efficacies (lumens produced per watt) remained poor (less than 15 lm/W).

More efficient fluorescent lights (patented already in 1901) were introduced commercially only in 1938 and they had eventually reached 100 lm/W (Rea 2000). Despite the inferior quality of their light (spectrally quite different from daylight) they eventually displaced incandescent light bulbs in offices, factories, and retail and institutional settings, and they became dominant in household use in low-income countries. Compact fluorescent lights were introduced during the 1990s and by 2018 the two types of fluorescent lighting accounted for about 55% of some 45 billion lights installed worldwide (Smallwood 2018).

Some countries have already enacted total or partial bans on sales of new incandescent lights but in 2019 United States scrapped the ban originally announced to begin in January 2020. The fastest recent transitions have been to halogen lights and to light-emitting diodes (LED). Halogens, whose spectrum is much closer to daylight, reached about half of all shipments by 2015, and LED, with efficacies already above 100 lm/W, will dominate new shipments in the early 2020s (Smallwood 2018). The transition from incandescent light bulbs to LED lighting will have thus taken nearly 150

years, an example of a particularly strong inertia for such a ubiquitous modern artifact.

Electric lights, particularly in combination with other electric and electronic devices, have changed many aspects of human behavior and have many undoubtedly positive effects by extending time available for work, education, pastimes, and exercise. Their economic impacts have been no less profound, with positive effects ranging from improved labor productivity and better workplace and transportation safety to extended business hours in retail and more flexible management of household chores. But electric lights also have negative impacts and it is no exaggeration to conclude that affluent societies now generate too much light, indoors and outdoors.

Nighttime satellite images show extensive areas of darkness only in parts of sub-Saharan Africa, Tibet, Mongolia, the western Amazon, and the high Arctic, while in many regions artificial lights are now forming large contiguous blobs or ribbons. The largest concentrations of nighttime lights are in the US Northeast, Florida, and California; in northwestern Europe; and in Japan ([NASA 2018](#)). Indoor lights have also demonstrably negative effects: notably, widespread sleep deficits induced by the abolishment of natural darkness and by addiction to screens.

The second most notable electric transition has been the conquest of industrial production by electric motors ([Schurr 1984](#)). The epochal substitution of animate energies by inanimate power (muscles by steam engines) retained the basic mode of transmitting mechanical energy required to operate factory machines. Power from a manually actuated large wheel or from a treadle moved by a foot was transmitted by a belt—as was the power from steam engines. Their reciprocating movements could be easily converted into circular motion but the best solution to transmit power from a centrally located large steam engine was by drive belts.

Long leather belts were led through openings in ceilings to individual floors to rotate master shafts placed near the ceilings and shorter belts then transmitted shaft rotations to individual work stands. This system had a number of obvious disadvantages. All drive belts were running at the same speed and only cumbersome belting arrangements could deliver different speeds to individual machines. Slipped belts (commonly unsheathed) could injure workers; belt operation was noisy and, due to considerable friction, inefficient. Factory floor plans were dictated by belt placement, and a

slippage of a single transmission belt or a crack in a shaft halted the entire assembly. And even if only some of the machines were in use, the entire transmission assembly had to be in motion. Electric motors changed all of that.

Appropriately sized electric motors could power individual machines, eliminating the risks of injuries. Noise and friction losses were gone, as motors directly rotate machine shafts. Machine operations can be individualized and productivities can be maximized, thanks to precise controls. Designs can be optimized for the most rational operation flows or for manufacturing flexibility. And getting rid of overhead rotating shafts made it possible to install superior lighting and later also air conditioning, which helped to increase labor productivity.

Transition from steam engines to electric motors in US industrial production was largely accomplished in just three decades, between 1899 and 1929, as the total installed capacity of electric motors increased almost 60-fold, while the total mechanical power had only quadrupled ([Daugherty 1928](#); [Schurr 1984](#); [Hunter and Bryant 1991](#)). In 1899 77% of all manufacturing power was in steam engines and 21% in water turbines, while the share of electric power in the country's manufacturing equipment was just short of 5%. In 1929 capacity of electric motors was 82.3% of the total; by 1969 the rate rose only marginally to 85%, with diesel engines and gas turbines supplying most of the rest. This transition was the most important factor in the near-doubling of US manufacturing productivity between 1899 and 1929, as well as in its further doubling by 1960 ([Schurr 1984](#)).

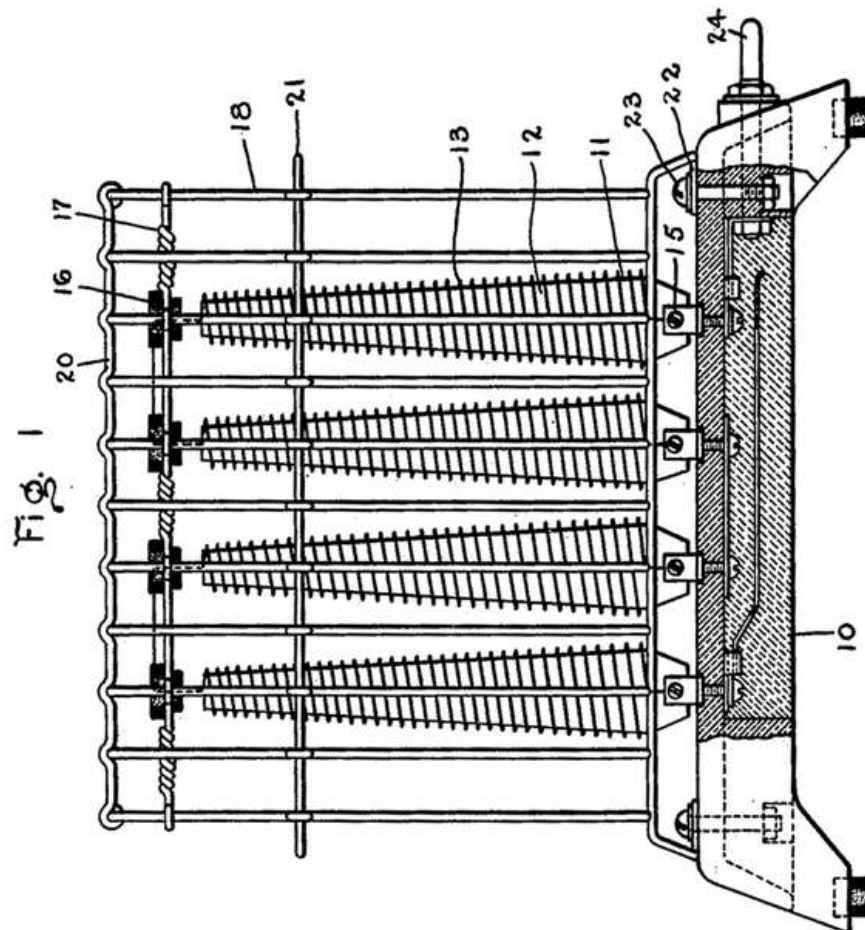
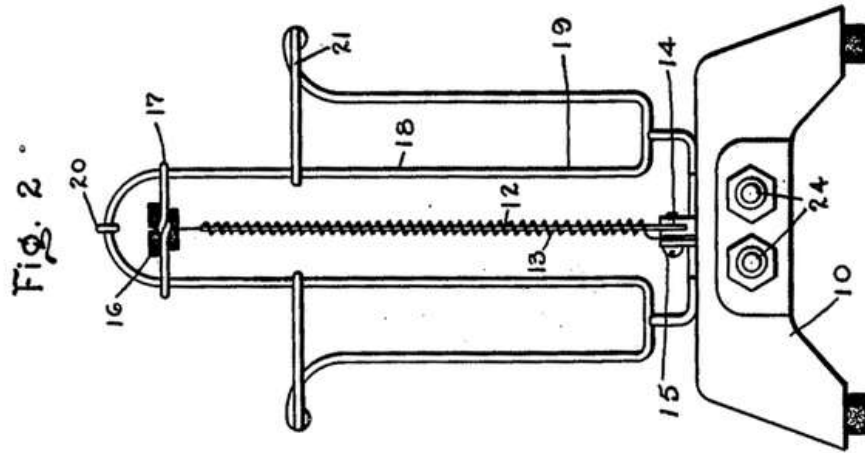
The first wave of household electrification, between 1882 and 1914, was slow and it was dominated by the adoption of electric lights, usually a centrally placed low-power light bulb (15–30 W) per room, but not necessarily in every room. Some better-off households bought a few small electric gadgets: a ceiling fan, a lightweight electric iron, and the first toaster ([Smil 2005](#); [Figure 4.9](#)). Subsequent diffusion of major electric appliances and devices proceeded at specific rates determined by a combination of factors, including technical maturity of newly available artifacts, their cost, and the cost of electricity, as well as by living conditions and lifestyles. Inevitable lags between introducing a product and the beginning of its commercial diffusion extended in some cases to

decades rather than years, and data about the progress of ownership show different rates of market penetration.

F. E. SHAILOR.
ELECTRIC HEATER.
APPLICATION FILED JULY 12, 1909.

950,058.

Patented Feb. 22, 1910.



WITNESSES:

Hester H. Fulmer
J. Ellis Elin

INVENTOR

FRANK E. SHAILOR.

BY *Alfred G. Davis*
ATTY.

Figure 4.9 Frank Shaylor's patent for "electric heater" was granted in 1910 and General Electric began to produce the first widely used toaster a year earlier. Image from the US Patent Office.

The range was the first kitchen appliance to go electric. By 1920 20% of all US households owned one, half of them just before World War II (1940) and 90% by 1955. Range ownership is now virtually universal but some households prefer gas ranges. Clothes washers began to diffuse only during the mid-1920s, their ownership fell during the WWII years, the 50% adoption mark was not reached until 1964, and the diffusion stopped short of 90%. In contrast, the rise of refrigerator ownership began at the same time but it followed a steady high rate of growth that brought it to 50% during the early 1940s and to 90% by 1953; since 1960 a refrigerator has been in virtually every American household. In Europe and in Japan refrigerators and clothes washers are as common as in the United States but because of higher electricity prices, clothes dryers remain rare.

Three major electricity converters began to diffuse only after World War II. Sales of window air conditioners took off only after 1960 and by 1974 half of all households were air conditioned, increasingly by central units (Nagengast 2002). Air conditioning made the US Sunbelt comfortable for the northerners who have been moving south in large numbers since the 1960s (Glaeser and Tobio 2007). At the same time, ownership of air conditioning was diffusing northward as central AC units were installed in new houses even in Minnesota and North Dakota: by 1990 air conditioning was in about 95% of all US households.

Among affluent countries only Japan and Taiwan have similarly high rates of AC ownership, and relatively inefficient window units are now attached to just about every urban apartment in warmer regions of China, with the national rate at about 60%, yet another example of how later starters can accelerate the transition to universal ownership. In 1990 a typical Chinese household owned just one or two electric fans; in the year 2000 urbanites had 31 air conditioners per 100 households. By 2010 the

urban AC rate reached 100, it rose to 142 in 2018 (as many families added a device to the second room), and in that year even the rural rate reached 65/100 households ([NBSC 2019](#)).

But residential space cooling remains uncommon in France and Germany (with units in fewer than 5% of households) and the rates are only about 20% in Mexico and Brazil, only a few percent are in India, and cooling is absent outside affluent parts of the cities throughout sub-Saharan Africa. The potential for future expansion is thus enormous and without any substantial progress in typical conversion efficiencies air conditioning could claim the single largest share of global electricity demand in buildings, accounting for more than a third, compared to a quarter required by residential appliances, and the total number of AC units may surpass five billion ([IEA 2018a](#)).

Uses, Efficiencies, and Intensities

Increasing efficiencies of energy conversions have produced impressively lower energy intensities, as the same amount of economic output, or a comparable mass of an industrial artifacts, are now generated with a fraction of energy inputs required decades ago. This has been a universal trend, with expected national differences, and for some specific uses its effect has been strong enough to reduce absolute growth rate to a minimum (or even to prevent further growth of demand) despite the still increasing size of the overall market.

Overview of energy uses

Combustion converted wood, and later coal, to thermal energy for cooking and heating. Coal's conversion to coke produce displaced charcoal, severed the dependence of ironmaking on woody phytomass, and allowed the metal's output to rise by many orders of magnitude. The second important diversification was to produce coal gas for outdoor and indoor lighting (and some heating) in major industrializing cities. This transition was followed by coal's rapid adoption for mobile uses, in land and water-borne transportation: its dominance was firmly established by the 1850s, and it lasted almost exactly 100 years before it was terminated by the rise of

refined fuels. The fuel's widespread use for indoor heating and for supplying processing heat for industries ended at the same time. Coal has been left with only two major markets, electricity generation and coke; the first of those uses has been in accelerating retreat in the United States and in the European Union, but it will retain its importance in China and India for decades to come.

Three key shifts in fuel uses have included increasingly indirect consumption due to the rising conversion to electricity (in 1900 less than 2% of fossil fuels were converted to electricity; in 2000 the share reached about 25%); a universal transition toward a higher share of fuels used in transportation; and rising shares of energy spent by households not only on home comfort but also outside the homes on activities ranging from more frequent eating out and travel. In 2015 about 54% of all extracted coal was burned in electricity-generating plants, but the share was nearly 90% in the United States and 46% in China ([OECD 2018a](#)). China is by far the largest producer of coal-fired electricity but its manufacturing also continues to rely heavily on the fuel (it supplied 65% of the sector's energy in 2017).

In 2015 less than 10% of the global fuel supply was consumed by ferrous metallurgy and less than 15% by other industrial uses. In contrast to coal, the use of refined liquid fuels ranges from lighting (kerosene lamps are still widely used in India) to lubricants, and from heating to petrochemical feedstocks. But refined-oil products now end up overwhelmingly as transportation fuels: recent global share has been about two-thirds (and 76% in the United States), with motor vehicles claiming the largest share of that total (in 2015 77% worldwide, 87% in the United States), followed by aviation and shipping.

These realities are not going to change fast. There are no readily available alternatives for long-distance commercial flying and for mass-scale intercontinental shipping. As a result, turbofans and diesel engines will be with us for decades to come ([Smil 2010a](#)). The second key consideration is the scale of transportation demand: 2.5 Gt of refined products could not be displaced rapidly even if many alternatives were readily deployable. And all fossil fuels also have important non-energy uses. In 2015 those applications accounted for less than 2% of the world's coal supply, but for 16% of refined oil products and for about 5% of natural gas ([OECD 2018a](#)).

Perhaps the best way to appreciate the magnitude of the transition to the modern high-energy society dependent on fossil fuels is to note how much they had multiplied during the 20th century and what the relative gains were between 2000 and 2020. My calculation of final energy uses (after processing losses) shows the following supply multiples between 1900 and 2000: 4.7 for coal, 199 for crude oil, and 538 for natural gas, resulting in a roughly 15-fold rise of fossil-fuel consumption ([Smil 2017b](#)). And the first two decades of the 21st century saw further substantial gains of coal and hydrocarbon use, with gains of just over 70% for coal, about 25% for crude oil, and more than 60% for natural gas ([BP 2020](#)).

These increments clearly indicate that the transition to fossil fuels has yet to be completed on the global scale, and even those long-range forecasts that indicate gradual decline of coal extraction project substantial additional demand for hydrocarbons before the middle of the 21st century ([Smil 2017a](#)). All but a small share of this growth will take place in Asia and Africa, but absolute supply of primary energy is expected to increase in the United States, Canada, and Australia. Unlike in Japan and in nearly all of the EU countries, those three economies still experience large immigration-driven population growth that translates into further increases of absolute energy supply. But the situation is quite different in relative terms, as all leading Western economies have reached per capita consumption plateaus that, in many of them, have been followed by slight declines in demand.

Per capita energy use at the end of Europe's wood era during the first half of the 19th century was as low as 15–20 GJ/year in the Mediterranean countries and as high as 150 GJ/year in heavily wooded Scandinavia. During the early decades of the 20th century it rose to more than 50 GJ/year in France and above 150 GJ/year in both the United Kingdom and the United States ([Kander et al. 2013](#); [Schurr and Netschert 1960](#)) and recent averages in the European Union's leading economies were mostly 150–160 GJ/capita (the Japanese rate was similar), while the US and Canadian means were above 300 GJ/year ([BP 2020](#); [UN 2019a](#)). These differences are not surprising, as similar levels of affluence (GDP or disposable income per capita) may require different levels of energy consumption because of the disparities in country size, climate, dominant life styles, and structure of national economy.

Despite these differences, per capita energy use in all Western countries is now either flat or has seen substantial declines. Onsets of national

saturation levels have differed. In Canada the leveling off began as early as 1980 (when the mean reached a high level of about 330 GJ/capita); in the United States, Germany, and France in 1990 (after reaching, respectively, just over 300 GJ and about 160 GJ/capita); Japanese consumption peaked at close to 170 GJ/capita in the mid-1990s, and Australian per capita energy supply has stagnated since the year 2000 ([World Bank 2019](#)). In all of these cases the transition of per capita energy use now seems to be complete.

Long-term trajectories of aggregate and per capita energy use do not capture the true extent of actual consumption gains and resulting economic and quality-of-life benefits. To do that we have to account for increasing efficiencies of energy conversions. Published comparisons generally neglect to do that but this efficiency gain has been a fundamental part of energy transitions as increasing efficiencies of every kind of energy conversion have been reflected in declining intensities of energy use and helped to reduce environmental impacts.

Efficiencies of energy use

Transition toward higher efficiencies has been the most common and the most rewarding component of modern energy development: it has made energy uses more widely affordable, declining energy prices have left a larger share of disposable incomes for increased discretionary spending, and the world consuming energy with efficiencies that prevailed in 1900 would be an intolerably polluted place. The shift toward higher conversion efficiencies has been due to gradual improvement of established conversions and to adopting innovative solutions.

Both of these gains can be illustrated by the long history of steam engines ([Smil 2005](#)). Their first, early-18th-century (non-condensing) designs had efficiency less than 1%. By 1800 Watt's famous improvements boosted that to no more than 2%, and subsequent innovations raised the typical efficiencies to 6–8%, with some large machines surpassing 15%. But it was quite impractical to build monstrously large efficient machines, and they were swiftly displaced by steam turbines and diesel engines whose gradual improvements have raised their best efficiencies to, respectively, more than 40% and just over 50%.

Indoor heating provides an excellent example of stepping up the ladder of increasing efficiencies with every new converter, going from less than 25%

for traditional wood stoves to no more than 45% for coal stoves, 65% for oil stoves, more than 70% for early natural gas furnaces, and in excess of 95% for their latest designs ([Smil 2017a](#)). And when measured in terms of fuel consumption per pkm the latest Boeing (787-9) is about 70% more efficient than the first commercial Boeing aircraft (707 in 1958).

What is much more difficult to do is to calculate the progress of national or global efficiency gains. This calculation can be done fairly reliably only for recent decades. The global balance prepared by the International Energy Agency shows that 50% of primary energy supply is now converted to useful energies providing heat, light, and motion ([OECD 2018a](#)). My historic reconstructions show that in 1950 the average efficiency of global energy use was no more than 35% and that in 1900 it was less than 20% ([Smil 2017b](#)). This statistic means that during the 20th century the worldwide production of primary commercial energies increased 16-fold but the availability of useful energy has gone up more than 40 times.

Those affluent nations whose energy consumption in 1900 was already dominated by coal now get at least twice and up to three times as much useful energy from a unit of primary supply, while the difference for countries that in 1900 still relied on phytomass fuels converted with low efficiencies is that the gain has been commonly five- to eightfold. Even so, the transition to high-energy-efficiency society still has a long way to go. While some converters are about as good as they can get (large electric motors, combined-cycle gas turbines), others can be considerably improved and in many other cases higher efficiencies can be achieved by a system redesign rather than by introducing new superior converters.

A new generation of gasoline car engines that operate more like a diesel is an excellent example of further possible gains. Traditionally, there was a large efficiency gap between automotive gasoline and diesel engines (with typical rates of, respectively, 20–25% and 35–40%) but the best current designs (such as [Mazda's Skyactiv-X](#)) have almost closed it ([Mazda 2018](#)). Efficiency opportunities through redesign are ubiquitous: natural-gas furnaces are already as good as they can get (95%+) but if all of them would be installed in super-insulated passive solar houses (including triple-pane windows filled with argon) consumption of primary energy per unit of useful heat can be reduced by at least 10–20%.

Energy intensities

Three transitions have interacted to produce declining energy intensities. New energy sources could be converted with much lower losses by new machines; new energy sources used by new, or greatly improved, industrial processes lowered specific energy requirements of products; and new macroeconomic arrangements have helped to optimize energy uses on unprecedented scales (all the way to the global level) and hence to minimize overall energy expenditures. Here are just three representative examples of major shifts in each category.

External combustion (burning coal in a boiler to generate heat for a steam engine) could never approach the efficiency of burning diesel fuel in an internal combustion engine. Only slightly more than 10% of energy consumed by a coal-fired oceangoing steam liner was transformed into useful mechanical energy—while the share for large diesel engines powering massive container ships is about 50%. Moving from coal-based to natural-gas-based synthesis of ammonia and deploying better compressors and more effective catalysts reduced the energy cost of ammonia synthesis by more than 70% ([Smil 2014](#)). And new tanker designs and new global trade arrangements made it possible for LNG to replace coal for heating in distant countries (exports from Alaska to Japan pioneered this option in the 1960s) and do so profitably and with reduced environmental impact ([Smil 2015a](#)).

There is no simple way to quantify the extent of the transition from high to low energy intensities. Energy requirements of material production have obvious physical (thermodynamic, stoichiometric) minima and in such cases the intensity transition is fully accomplished once the actual energy expenditures have come close to such immutable values. For example, synthesis of ammonia by the Haber-Bosch process used to require more than 100 GJ/t of ammonia, while today's most efficient plants need just 27 GJ/t: that is, less than 20% above 20.9 GJ/t, the stoichiometric energy requirement for methane-based ammonia synthesis (IETA 2018; [Smil 2001](#)). At the same time, it must be realized that a closer approach to a thermodynamic minimum might be technically possible but that it might be unacceptable due to excessive costs.

The best practices of steelmaking are now similarly advanced. [Fruehan et al. \(2000\)](#) put the practical minimum expenditures for integrated steelmaking (blast furnace, basic oxygen furnace, hot rolling) at 19.5 GJ/t compared to the best reported values of 25.5–27.9 GJ/t: that is, within 25%

of the achievable minimum. Increasing shares of steel are now made in electric arc furnaces by melting scrap metal and the practical minimum for this process is about 1.6 GJ/t compared to 2.1–2.4 GJ/t in practice, once again, within 25% of the best possible performance. In contrast, the minimum for making basic soda-lime glass is 2.8 GJ/t, and borosilicate and crystal glass needs at least 2.35 GJ/t, while typical energy requirements in modern plants are (at 5.8–9 GJ/t) two to three times higher (IETA 2018).

Quantifying declining energy intensities of overall economic product is even more complicated. We could not have reached today's prosperity if our economies had required the same amount of energy per unit of output as they did just in 1970, to say nothing about the rates of 1870. But the measure works best when following its trajectories for individual nations, although even there it requires a deeper understanding of specific circumstances. Its quality depends on accurate reconstructions of past aggregate energy and economic data and hence perhaps its best long-term values are those for the United Kingdom, the United States, and Japan. Rather than citing absolute rates I review their transitions in relative terms ([Figure 4.10](#)).

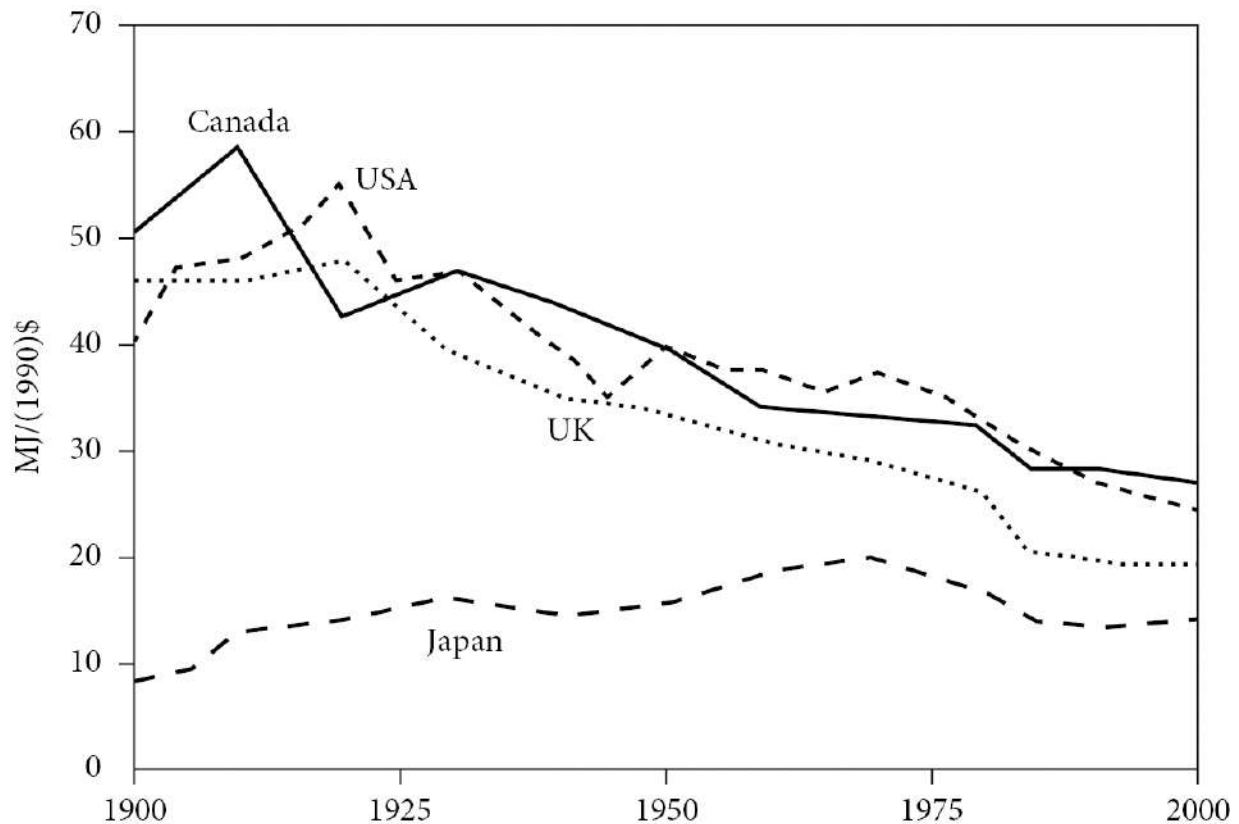


Figure 4.10 Declining energy intensities of national economies: a universal trend tending toward a similar outcome. Based on [Smil \(2017a\)](#).

The United Kingdom's energy intensity rose in the early stages of industrialization by at least 40%; it peaked around 1880 because of the rapid development of energy-intensive mining, ferrous metallurgy, and heavy manufacturing; and then it began a steady gradual decline (interrupted only by wartime or postwar dips or spikes) that brought it to only about 20% of its peak value by the beginning of the 21st century ([Warde 2007](#)). Reconstructions for several major European economies show long-term convergence for countries whose intensities differed by as much as a factor of three in 1860, with Sweden having the highest and Italy the lowest energy intensity. By the year 2000 those two countries, as well as Germany, the United Kingdom, France, Spain, the Netherlands, and Portugal had very similar energy intensities with the 20th-century declines ranging from more than 70% for the United Kingdom and Sweden to less than a third for the Netherlands and only about 10% for Italy ([Kander et al. 2013](#)).

And the trend is continuing: between 1990 and 2015 energy intensity of the EU countries declined by a further 35% (45% in the United Kingdom, 24% in France, 14% in Italy), a continent-wide shift that led the European Environmental Agency to ask, “Has there been absolute decoupling of economic growth from energy consumption in Europe?” (EEA 2018). And Europe has not been alone; during the same period the Russian intensity fell by about 30%, the American by 35%, and China’s by two-thirds. But any simplistic comparison of relative national declines (for example, concluding that China has done much better than the United States or France) would be misleading.

All national intensities must be seen in proper historical context. China’s impressive post-1990 energy intensity decline has been largely a catch-up phenomenon, with rapid economic modernization making up for decades of Maoist delusory policies, and it has been aided by a significant shift from heavy industries to mass-scale manufacturing of consumer goods for export. In absolute terms the country’s economy is still more energy intensive than that of the United States or France, with the mean 2015 rates being, respectively, 6.7, 5.4, and 4.1 MJ/\$2011 ([World Bank 2019](#)). Most importantly, in China’s case, benefits of falling relative energy intensities were overwhelmed by rapid growth of total economic product (nearly 11-fold between 1990 and 2015), a trend that led to boosting total primary energy supply 4.4-fold during the same period: obviously there has been no decoupling of the two processes!

In contrast, absolute energy consumption rates in the United States and France were, respectively, only about 15% and 10% higher, reflecting already very high levels of per capita use (and, as already noted, stagnation and even decline of per capita supply) as well as the recent trend of deindustrialization, as energy-intensive activities have been offshored, largely to Asia. In any case, decline of energy intensities has been a worldwide phenomenon but, given the different structures of national economies, there is no universal minimal rate to which these falling rates might be trending. Not surprisingly, calculating energy intensity for the global energy use is even more problematic. Reconstruction of past national GDP values is often questionable and the aggregate of energy supply contains countries spread across the entire spectrum of economic development.

Using the most often cited estimates of global economic product for 1900 and 2000 ([Maddison 2007](#)) and my reconstruction of the 20th-century energy supply shows that the global intensity rose by about 20% between 1900 and 1970 and by the year 2000 declined to almost the same level as in 1900. Data for 99 countries between 1971 to 2010 and additional analysis of some older historical data imply that energy intensity has tended to decline in countries that have become richer but not in others ([Csereklyei et al. 2016](#)). Moreover, since the early-19th-century energy intensities have been converging toward their current distribution as per capita energy and energy quality have been increasing and as the cost share of energy has been declining.

Further decline of global energy intensities is certain but, even more so that in specific national cases, we cannot offer any minimal level that could be seen as the accomplishment of energy intensity on the worldwide basis. And the process is always self-limiting: as already noted, many key productive activities are already approaching their minimal energy requirements. The unfolding transition from fossil fuels to renewable energies should bring further declines in overall energy intensities as more conversions will be electrified. At the same time, too many recent expectations regarding this transition have assumed that it could be accomplished in relatively short time. That is a fundamental misunderstanding of the very nature of energy transitions: they always take decades to unfold.

5

Economies

An array of economic contrasts between pre-transition societies and modern affluent states is far too large to be addressed fully in a single book chapter. Of course, two fundamental differences have been already dealt with in some detail: characterizing modern affluent economies as societies enjoying a surfeit of food, fuels, and electricity would be a functional definition that even some economists might find satisfactory. Going beyond these key contrasts can be done by focusing on three principal categories of growth, structure, and abundance. Once again, data for high-income countries can take us back a couple of centuries, but accelerated economic transitions of late starters deserve appropriate coverage.

We can conclude, with very high confidence, that economic growth during antiquity, the Middle Ages, and the first two centuries of the early modern era (1500–1700) remained quite low, mere fractions of a percent. The structure of traditional economies was, necessarily, very similar, with all but a small share of the population engaged in subsistence food production and the remainder working in artisanal manufacturing, construction, and transportation, with the smallest share being ruling and educated elites. Abundance—be it of food, material possessions, or desired immaterial experiences—was only for small privileged strata in relatively well-off societies. In a few pre-transition societies that exclusivity began to change during the 17th and 18th centuries.

Holland of the Golden Age (1608–1672) and Edo, the capital of Tokugawa Japan (1603–1868), are perhaps the best occidental and oriental examples of more widely encountered (one might say incipient) material affluence and a growing diversity of pastimes ([Schama 1997](#); [Nishiyama 1997](#)). But the three fundamental markers of economic transition—rising growth of output, profound structural shifts, and the arrival of mass-scale consumption of products and experiences—became clearly and widely discernible only as population, dietary, and energy transitions combined

with technical innovations and with better modes of governance to start a new era of unprecedented economic advances.

End points or asymptotic levels indicating the completion of demographic, dietary, and energy transitions are either self-evident or can be well defined. There can be no doubt that a society has completed its demographic transition once its fertility rates have declined below the replacement level and remained there for decades; that it has gone through its dietary transition once its supply of food has greatly surpassed even the highest conceivable nutritional requirements and has generated an unacceptably high level of waste; and that it has accomplished its energy transition when it consumes no traditional phytomass fuels and relies solely on a mixture of fossil fuels and primary electricity consumed at high per capita rates.

In contrast, there are no indications that certain (no matter how high) per capita levels of economic product or of disposable income should be seen as markers of accomplished economic transition. There are no national economic policies aiming at a mere maintenance of average per capita output or income. And calls for steady-state economies—whose aggregate growth would be high enough only to cover any population increments and, in the case, of stable or declining populations the annual economic growth would be then zero or it would be slowly declining—remain largely limited to the proponents of ecological economics.

Even in the world's most affluent societies there are constant concerns about maintaining the highest possible growth rates. Even in large mature economies, where one should not expect high rates of GDP growth, annual gains of 2–3% are seen as much preferable to anything less than 1%. This quest has, so far, translated into no obvious limits where abundance is concerned. The average size of an American house is now 2.5 times larger than it was in 1950, and it is still slowly increasing. Moreover, the success of Amazon Prime shows that there is no imminent limit as to the number of items people wish to acquire (and do so instantly). Only with structural elements is it easy to pinpoint transition phases. The outcomes will show inevitable national specificities, but general quantitative thresholds are obvious ([Figure 5.1](#)).

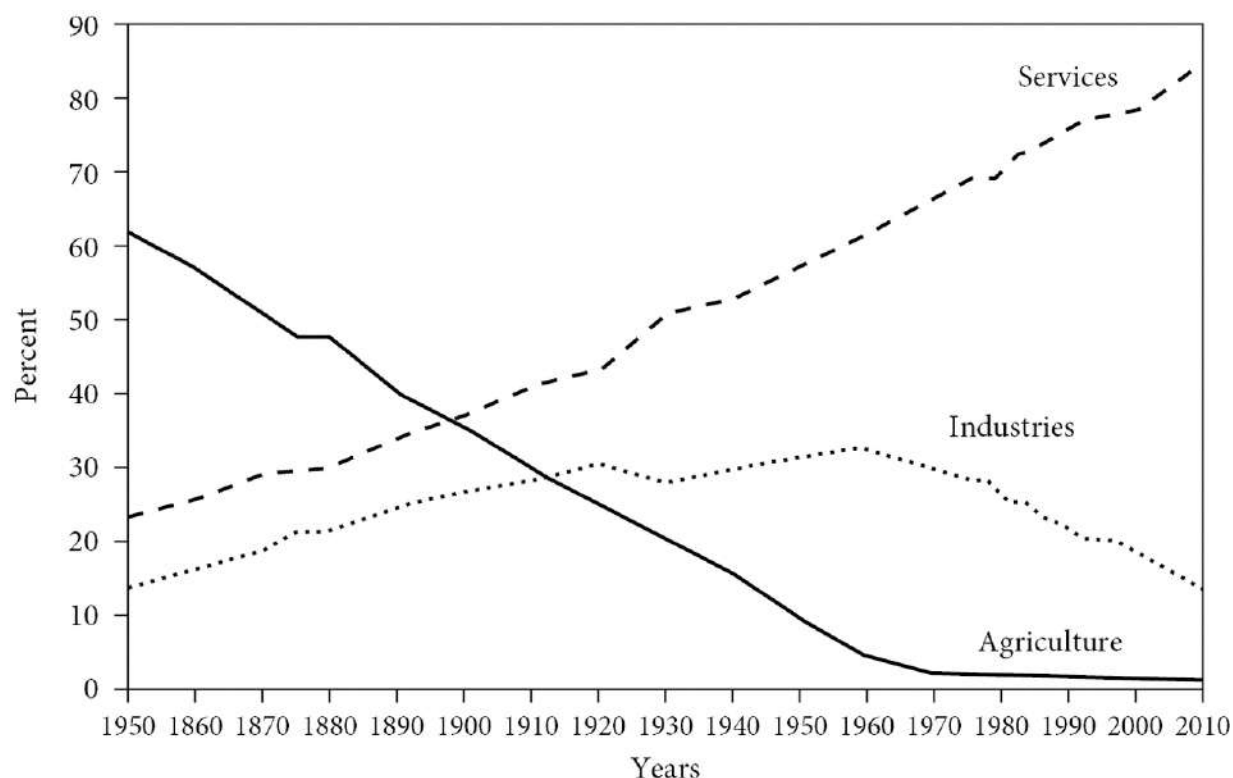


Figure 5.1 Changing sectoral composition of employment in the United States, 1850–2020. Based on [Sposi and Grossman \(2014\)](#).

Traditional economies employed more than 80% of their populations in food production; now the shares in all affluent economies are less than 5% ([World Bank 2019](#)). Consequently, there can be no doubt that that particular transition has been accomplished in the United Kingdom and Germany (where agriculture now employs just 1% of the labor force) as well as in the United States, Sweden, and the Netherlands (where the 2017 share was 2%), or France and Japan (at 3%); that it is quite advanced in China (18% in 2017) and still has a long way to go in India (43%); and that it is in its early stages in Uganda (69%) or Rwanda (66%). Similarly, there can be no argument about the nearly accomplished shift of labor from manufacturing to services when even in the United Kingdom, the world’s first industrialized economy, less than 10% of GDP now comes from making goods.

Economic transitions are constrained by universal commonalities dictated by energy and material requirements and by the limits imposed by natural and technical factors. Beyond these physical constraints there have been large differences in the speed of economic transitions and in the extension

of their benefits to the majorities of affected populations. Tracing these remarkable national idiosyncrasies of the three constituents of economic transition—growth, structure, and abundance—reveals their specific historically or culturally determined causes.

Post-1990 economic literature is full of studies of economic transitions that refer to the process of moving the former Communist (centrally planned and highly autarchic) economies to some forms of “free market” arrangements and integration in the global economy ([Weitzman 1993](#); [Pistor 2013](#)). These are the second-order transformations because the USSR and Europe’s pre-1990 Communist economies had already undergone the transition from agrarian to industrialized economies, and although they lagged behind the West in extending the benefits of abundance to their populations they were clearly moving along a similar trajectory.

These secondary transitions are not the focus of this chapter, in which I will be concerned with the historical process of moving from traditional patterns of low growth, stagnant economic structures, and limited consumption patterns to modern systems that emphasize growth and structural transformations and that are characterized by mass material consumption, high mobility, and information and communication overload. China presents an obvious hybrid case, as its recent transformation has combined the elements of both the first- and second-order economic transitions.

Growth of Economic Output

Prolonged stagnation or very low growth rates of traditional economies are not surprising, given the combination of the very slow growth of populations, the inability to lift food production consistently above the subsistence level, and the millennia-long reliance on the same sources of biofuel and on the same prime movers of limited unit capacity. Moreover, the slow pace of technical innovations did little to raise labor productivities or introduce new cultivation or manufacturing techniques. Given these realities, where did the sources of higher and more durable economic growth come from?

Remarkably, the mainstream economic analyses (concerned with capital and labor) have managed to ignore the most important physical factor, the

rising energy use and its qualitative changes. Ayres showed convincingly that energy is a far more important factor of production than is indicated by its small cost share, and that the onset of modern economic growth can be traced largely to declining energy costs caused by the discovery and exploitation of inexpensive and highly energy-dense fossil fuels (Ayres et al. 2013; Ayres 2016 and 2017). The history of this process was already reviewed, and in this chapter I focus on the reconstruction of long-term economic growth and on its explanations.

These reconstructions are tentative even for the early modern era, and for the preceding epochs they are nothing but approximations that might get the relative ranking right and capture the basic qualities of the process. But even that may be too much to ask, as is well illustrated by the already noted fundamental disagreements about the relative achievements of pre-1750 Chinese and European economies between Frank (1998) and Pomeranz (2000) on one hand and Maddison (2007) and Broadberry et al. (2014) on the other. One thing that such major disagreements do not change is the broad consensus that the annual rates of premodern growth remained well below 1%.

There was virtually no growth in central and northern Italy between 1300 and 1913 (Malanima 2011), and the rates were merely 0.03% for England between 1270 and 1663 (Broadberry et al. 2015) as well as for Spain between 1270 and 1850, 0.1% for China between 1020 and 1850 (Broadberry et al. 2014), and 0.22% for the Netherlands between 1348 and 1850 (van Leeuwen and van Zanden 2009). After hardly any growth before the early 17th century, English and then British data show an acceleration to about 0.8% during the late 17th century followed by a decline to less than 0.3% between the 1700s and 1760s and just 0.1% between the 1760s and 1780s; the annual rates remained just around 0.5% for the next 50 years and then came a rise to only about 1.2% between the 1830s and 1860s (Broadberry et al. 2014). Maddison's (2007) data show British per capita growth averaging 1.26% between 1820 and 1870. By that time the country was the largest modern economy, accounting for nearly 10% of the global economic product (slightly ahead of the rising United States) at a time when its population was just 2.5% of the global total.

Understandably, this epochal discontinuity has been the subject of numerous speculations, quantitative inquiries, and models as well of polemical critiques of previously suggested mechanisms that had tried to

explain this remarkable phenomenon. Why was Britain the first early modern economy to experience this takeoff of economic growth? What determined its timing? What factors had combined to sustain it? What were the respective roles of new energy sources, new scientific knowledge, new technical inventions, and new economic arrangements? Was it really a relatively rapid transformation justifying the name of industrial revolution or was it a more complex process of gradual economic modernization? Inconclusiveness of these inquiries is perhaps best illustrated by the fact that there has been no agreement even about the onset and the duration of that transformation. [Lilley \(1966\)](#) set perhaps the most liberal span for the country's industrial revolution by dating it between 1660 and 1918, [Ashton \(1948\)](#) restricted the range to 1760–1830, and [Rostow \(1971\)](#) pinpointed the takeoff period to 1783–1802.

Sources of accelerated growth

Perhaps the only incontrovertible conclusion is that we must leave behind that old simplistic thesis of the industrial revolution as the direct consequence of the invention and improvement of the steam engine. This concept has been in doubt for a long time. Industrialization is synonymous with the rise of the modern factory ([Mokyr 2001](#); [Freeman 2018](#)), but as [Musson \(1978, 141\)](#) noted, “the typical British worker in the mid-nineteenth century was not a machine-operator in a factory but still a traditional craftsman or labourer or domestic servant.” This theory was endorsed by [Sullivan's \(1990, 360\)](#) conclusion that “the British economy was largely traditional 90 years after 1760.” Even more radically, [Cameron \(1982\)](#) claimed that the very term industrial revolution is a misnomer, and [Fores \(1981\)](#) thought the very notion of a British industrial revolution to be a myth.

Nicholas von Tunzelmann showed that the impact of the steam engine was smaller and that it came later than was commonly believed ([von Tunzelmann 1978](#); [Bruland and Smith 2013](#)). The best recent study of the long-run impact of the steam engine's deployment shows that its contribution to economic growth was minimal before 1830 and that the widespread diffusion of high-pressure designs came only after 1850. As a result, “steam had its greatest impact on productivity growth in the second half of the 19th century, not during the industrial revolution” and that

“seeking to base an account of 19th-century British economic growth primarily on the implications of steam is surely misconceived. At no time is its impact large enough to dominate” ([Crafts 2014](#), 349–350).

Similarly, increased use of coal could not, on its own, bring the British acceleration. Coal was in widespread use long before it began to power numerous steam engines. During the 17th century it was used for household heating and cooking, by smiths, brewers, clothes dyers, and producers of lime and soap, and, thanks to the invention of reverberating (heat-reflecting) furnaces also to make glass and ceramics. After 1750 it was increasingly used to make coke for smelting iron ore in blast furnaces, and even before Watt’s engines began to sell in larger numbers during the 1780s the fuel supplied more than 80% of Britain’s thermal energy.

[Tepper and Borowiecki \(2015, 231\)](#) concluded that the two proximate causes of the shift away from land “were the twofold increase of total factor productivity growth combined with and even greater decline in the economy’s dependence on land from 1780 to 1860.” Total factor productivity (TFP) was an important factor in the British breakout. TFP refers to the share of economic growth that cannot be explained by accounting for labor and capital inputs and that reflects advances and innovations in production techniques. Foundations for its study were laid down in the late 1950s and the early 1960s ([Abramovitz 1956](#); [Solow 1957](#); [Kendrick 1961](#)) and it has become a critical concept in modern evaluations of economic growth ([Pasinetti 1981](#); [Arena and Porta 2016](#)). In modern economies it has been often the single most important factor explaining their expansion ([Shackleton 2013](#)).

As for the declining dependence on land, attentive readers remember [Chorley’s \(1981\)](#) quotation referring to the British agricultural revolution: labor surplus created by rising agricultural productivity released workers for urban and industrial employment as the nation’s share of population in agriculture fell to 37% by 1760 and to 24% by 1841. Compared to these two factors neither expanded coal extraction or trade had the same immediate impact. Contrary to traditional perception of a rapid and multifaceted advance, the first industrial revolution was a paradoxical combination of gradual acceleration of economic growth and pronounced industrialization of the labor force, but this gradualism “should not be confused with an absence of fundamental change. The hallmark of the

industrial revolution was the emergence of a society that was capable of sustained technological progress and faster TFP growth” (Crafts 1995, 533).

Two detailed and well-documented cases for two different paths to Britain’s primacy were offered by Robert Allen and Joel Mokyr. The briefest summary of Robert Allen’s conclusion is to quote from his book’s introduction: “The Industrial Revolution, in short, was invented in Britain in the eighteenth century because it paid to invent it there” (Allen 2009, 2). Allen’s argument is about relative conditions: Britain, unlike continental Europe, had relatively high wages but cheap capital and even cheaper coal, and this combination made it affordable to incur high fixed costs connected with the development of such epochal innovations as steam engines or coke-based pig iron production.

In contrast, Joel Mokyr, who has presented his explanation of the origins of the modern economy in three separate volumes of, I would say, increasing abstraction (Mokyr 2002, 2009, and 2017), sees culture as the deciding factor. In 2009 he concluded that Britain led because it was able to take advantage of its physical endowment “thanks to the great synergy of the Enlightenment: the combination of the Baconian program in useful knowledge and the recognition that better institutions created better incentives” (Mokyr 2009, 122). Eight years later he credited the Enlightenment as the decisive spark in politically fragmented Europe, where the new market for ideas was sustained by a transnational community (the Republic of Letters) that disseminated new scientific findings. “The big difference between Europe and the rest of the world was the Enlightenment and its implications for scientific and technological progress” (Mokyr 2017, 339).

Both of these grand explanations have demonstrable weaknesses. Enlightenment science was not behind every innovation and every technical advance of the era, and it would be difficult to transform even superior ideas into quotidian realities without abundant energy and without cheap capital. On the other hand, it is impossible to claim that every innovation was driven by the quest for profit (by saving labor) or that the combination of Britain’s relatively high wages and inexpensive coal sufficed to launch a new era. Nicholas Crafts, when reviewing Allen’s book and Mokyr’s 2009 volume, put it best when he concluded that the authors “see their accounts as competing. In essence, they are not mutually exclusive and perhaps

eventually will more appropriately be seen as complementary” ([Crafts 2010](#), 166).

And they should be complemented further by including other essential factors, including those that provided critical contributions to its initiation and that sustained it for generations. A model calibrated to new English occupational data for 1710 was able to match the location and magnitude of the spatial takeoff in the first industrial revolution, making clear the importance of the spatial concentration of economic activity and a relatively limited role for government to accelerate the date of industrial takeoff ([Trew 2014](#)). Both the quantity and quality of new energy supplies (bituminous steam coal, coking coal, larger waterwheels) provided a key (and insufficiently appreciated) precondition of any epochal progress. Nor should we minimize the effects of rising literacy, stronger institutional arrangements (patent and property rights), access to foreign markets, and, always, the impact that specific historical circumstances had on long-term economic development ([Nunn 2009](#)).

[Rostow \(1960\)](#) based his influential work on the stages of economic growth on the British historical experience and his choice is both understandable and arguable. Understandable because some aspects of the pioneering experience had to be, unavoidably, repeated by other nations, arguable because of the existence of significant national idiosyncrasies and because the transition to economic modernity cannot be subsumed by a single model. Britain was the first one to lead but not every national economy followed in the same footsteps, because

an economy does not necessarily need to look a certain way, or have a certain quantity of capital, level of education, set of industries, nor arrangement of institutions to achieve takeoff. Rather, wherever economy starts, modern growth is touched off by sustained but potentially temporary rapid productivity gains or other increase in maximum sustainable population growth ([Tepper and Borowiecki 2015](#), 231).

Trajectories of growth

Periods of sustained growth were experienced by other countries that had joined Britain in the quest for economic modernity. [Maddison’s \(2007\)](#) data shows several countries whose average annual growth of national GDP had surpassed, or had come very close to, the British rate between 1820 and 1870: Germany at 2.0%, Belgium at 2.24%, Norway at 2.25%, and the

United States at 4.2%. And between 1870 and 1913 the United Kingdom (averaging 1.9%) was left behind by at least a score of other countries, including not only most of the Western European economies (averaging more than 2%) and the United States (at nearly 4%) but also Japan (2.44%), the country whose economic transition began only during the 1870s after the restoration of imperial rule in 1868, following more than 250 years of the feudal Tokugawa shogunate ([Jansen 2000](#)).

Per capita GDP growth rates show the same trend when we compare all major Western economies and Japan with the United Kingdom. Except for the United States, between 1820 and 1870 their growth was lower than the British mean, but between 1870 and 1913, while the United Kingdom's average was 1.10%, France was advancing at 1.45%, Japan at 1.48%, and Germany at 1.61%, and the United States at 1.82%; major Latin American economies had also made substantial gains ([Maddison 2007](#)). But China remained a premodern state with average per capita GDP growth of just 0.1% between 1870 and 1913, the period that included the last 40 years of the last imperial dynasty that ended in 1911 and led to nearly four decades of instability and conflicts.

During the next period, between 1913 and 1950, economic growth was negatively affected by two world wars and by the world's deepest economic crisis. The United States managed per capita GDP growth rate of 1.6%, France 1.1%, and the United Kingdom and Japan about 0.9%, but German annual average was less than 0.2% and conflict-beset China had suffered a net economic decline. The years between 1950 and 1973, when OPEC (Organization of the Petroleum Exporting Countries) actions led to the quintupling of world crude oil prices, were the period of record-high economic growth in the West and in Japan, with annual average per capita rates ranging between about 2% for China and 2.5% for the United States and the United Kingdom to 3.5% for the USSR, 4% for France, 5% for the recovering Germany, and 8% for Japan, coming back from an even greater devastation. The closing decades of the 20th century were different. Per capita rates of economic growth declined in every advanced economy and the greatest pullbacks were in Germany (to 1.6%) and Japan (to 2.1%).

Crafts's (1999) retrospective of the 20th-century economic growth attempted to break down its sources in major economies among capital, labor, and total factor productivity. Capital was always the dominant factor in the United Kingdom, in Japan during the first half of the century and

again after 1973, and in Germany before World War II. TFP was the leading factor in the United States until 1973 but then it was surpassed by capital, and it dominated the post-1950 growth in Germany until the century's end. But even as growth of mature economies had slowed down after 1973 and as TFP contributions had weakened, important gains in an average standard of living continued with Japan making the greatest strides by matching, and surpassing, the average Western level as measured by the Human Development Index.

Several Asian economies had copied the Japanese experience by concentrating on specific manufacturing sectors in order to achieve temporarily rapid rates of growth. Taiwan had focused first on inexpensive consumer goods but had rapidly moved into higher value-added electronics. South Korea followed Japan with its development of large-scale ship building and car making and with its concentration on electrical and electronic products made by its industrial conglomerates (Samsung, Hyundai, LG). The influence of the Japanese model could be also seen in Singapore, Thailand, and Malaysia and more recently in Indonesia and Vietnam—as well as in China's delayed quest for modernity.

China's modernization trajectory is a perfect illustration of how a nation's history and politics matter because when the post-imperial turmoil had finally ended by the Communist victory in 1949, the country then went through three more decades of suffering brought by Mao Zedong's doctrinaire policies. They combined the Stalinist model of promoting heavy industries with suppression of urbanization and with severe limits on personal freedoms. The worst of all was Mao's delusionary attempt to do in a matter of years what other countries had achieved in decades. The Great Leap Forward, aimed at multiplying coal and steel output, led to the world's most devastating famine (1959–1961), and China's road to modernity began only with Deng Xiaoping's reforms in the early 1980s ([Smil 2004](#)).

The speed of China's post-1980 catch-up (most of it has actually taken place since 1990) remains impressive even after discounting many well-documented exaggerations in the country's official statistics and after taking into account many advantages of late starters with ready access to the latest innovation. In addition, this benefit was facilitated by sustained and massive net foreign direct investment that has been above \$50 billion a year since 2002 and that peaked in 2013 at \$290 billion ([World Bank 2019](#)). Annual per capita GDP growth has been above 5% since 1990, and the

average per capita GDP (in current international dollars) reached about \$17,000 in 2017, just ahead of Brazil. India, Asia's second largest modernizing economy, has grown much more slowly than China and most African countries can offer their citizens a standard of living that remains inferior even when compared to European levels of three generations ago.

The best way to compare the achievements of economic growth in per capita terms is to use constant (inflation-adjusted) monies and their purchasing power parities (PPP) that relate currencies according to their capability to buy a set number of goods and services. This is not a perfect choice but one that is superior to using often volatile official exchange rates. World Bank's database of GDP PPP values (in constant international dollars) begins in 1870 when the United Kingdom led with about \$4,800/capita and the United States averaged about \$3,900, France \$3,100, and Japan \$1,100. By 1900 the United States was just 3% behind the United Kingdom but France was still 30% and Japan almost 75% behind ([World Bank 2019](#)). By 2015 average per capita GDP rose eightfold in France, 20-fold in Japan, but only 5.4 times in the United Kingdom as the rates converged, with France at \$37,500 and the United Kingdom mere 2% and Japan just 5% behind, while the US mean rose just above \$52,000, or eightfold, since 1900. Chinese data begin in 1950 when the per capita mean was less than half of Japan's 1900 and had only doubled during Mao's rule. In 1980 the average was just over \$700, it doubled by 1990, and then it rose nearly ninefold to about \$13,000 per capita by 2015.

In 1990 both India's and Nigeria's per capita GDPs were ahead of China, with the Nigerian rate more than twice as large—but by 2015 the Chinese mean was more than twice as high as in those two economies and it put the country at the level that was reached by Japan in the late 1960s. At the same time, India's mean was comparable only to the French rate of the early 1920s, and the means of many sub-Saharan countries were no higher than some European averages of the late 19th century. How to explain this great divergence? Answers have ranged from cultural factors to geographic determinism, and from differences in historical legacies (independent polities vs. countries affected by colonialism and slave trade) to institutional and legal arrangements (forms of governments, property rights, patent laws).

The role of technical innovation (most writings prefer to use a less accurate but now standard term: technological change) and the propensity

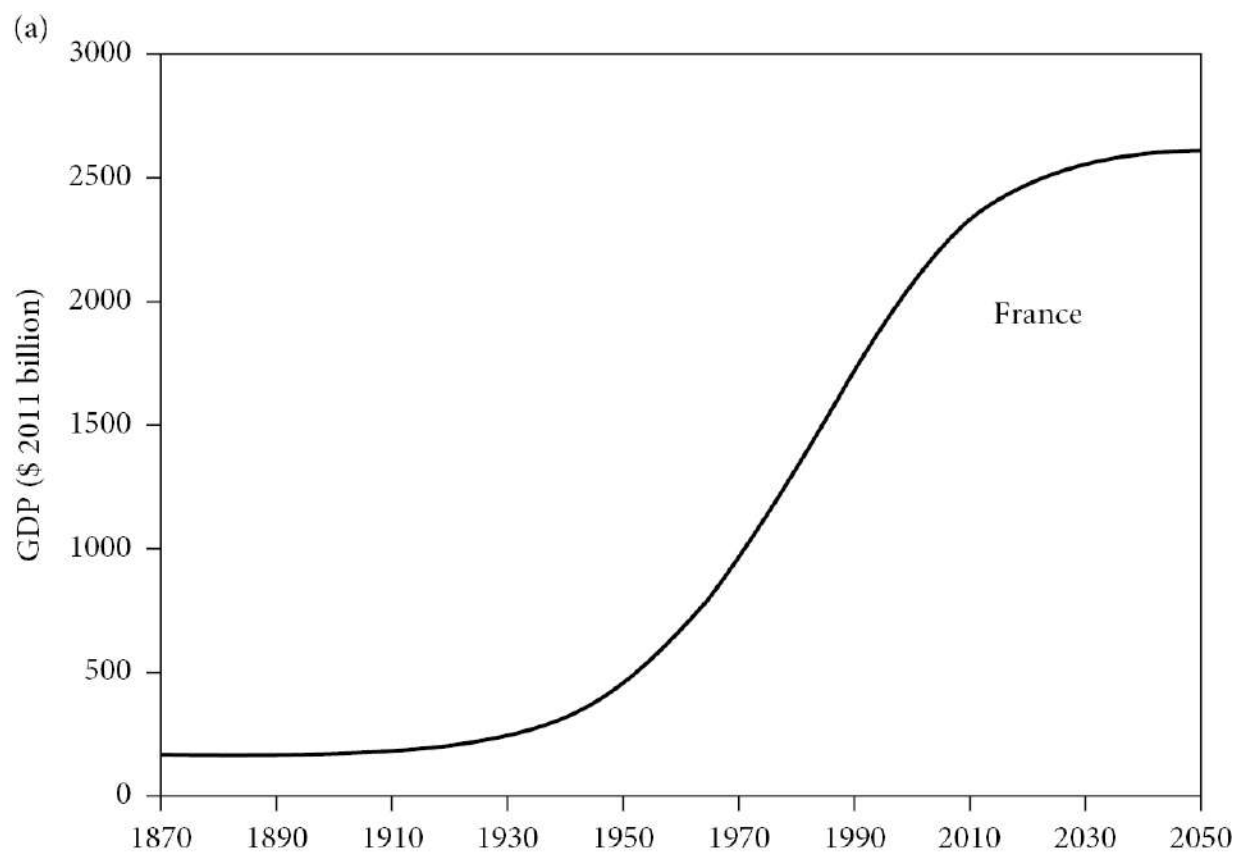
of its adoption and sustained pursuit have received much attention. [Allen \(2012\)](#) provided a convincing addition to this line of reasoning when he argued that much of this progress in raising labor productivity took place by increasing capital intensity, with new techniques finding ready acceptance only in high-wage economies. Allen's data show that between 1850 and 1880 substantial shifts in the leading countries led to capital-labor ratios of \$5,000–\$9,000 per worker, that they rose to \$9,000–\$12,000 by 1913 and to \$20,000 by 1939. The trend continued after World War II with the \$40,000 mark reached in 1965, \$73,000 by 1990 when the output per worker reached \$38,000, roughly four times as much as at beginning of the 20th century. Perhaps the most remarkable conclusion is that by the close of the 20th century the output per worker in the countries with low capital labor ratios was no higher than in countries with the same capital labor ratio as far back as 1820.

This finding means that during the last 200 years “the rich countries created the production function of the world that defines the growth possibilities of poor countries today” (Allen 2011, 1). Post-1990 China has advanced rapidly along that defined trajectory but no other populous country is likely to replicate that experience in coming decades. Between 2006 and 2016 China's GDP growth rate averaged 9%, India's 6%, and Nigeria, Africa's most populous country, lagged far behind with just 3% ([World Bank 2019](#)). Obviously, even with improved performance populous Asian and African economies will take decades to approach the current rates prevailing in the affluent nations.

Prospects for economic growth

Historical trajectories of national economies between 1870 and 2015 indicate that all major affluent economies have entered the era of declining GDP growth. They form symmetrical logistic curves that reflect many idiosyncrasies of national economic development but that have already passed their inflection points as their trajectories appear to be tending toward not-so-distant asymptotes ([Smil 2019a](#)). Italy had its inflection year already in 1974, Japan in 1979, France in 1981, the Netherlands in 1994, the United States in 1996, and Canada in 1997 ([Figure 5.2a–d](#)). Using these logistic curves to forecast 2050 values shows gains ranging from marginal (for France and Japan) to about 30% for the United States. In contrast, the

Chinese trajectory (starting in 1950) indicates the inflection year only in 2016 and the country's GDP could be twice as large in 2050, compared to 2015 ([Figure 5.2](#)).



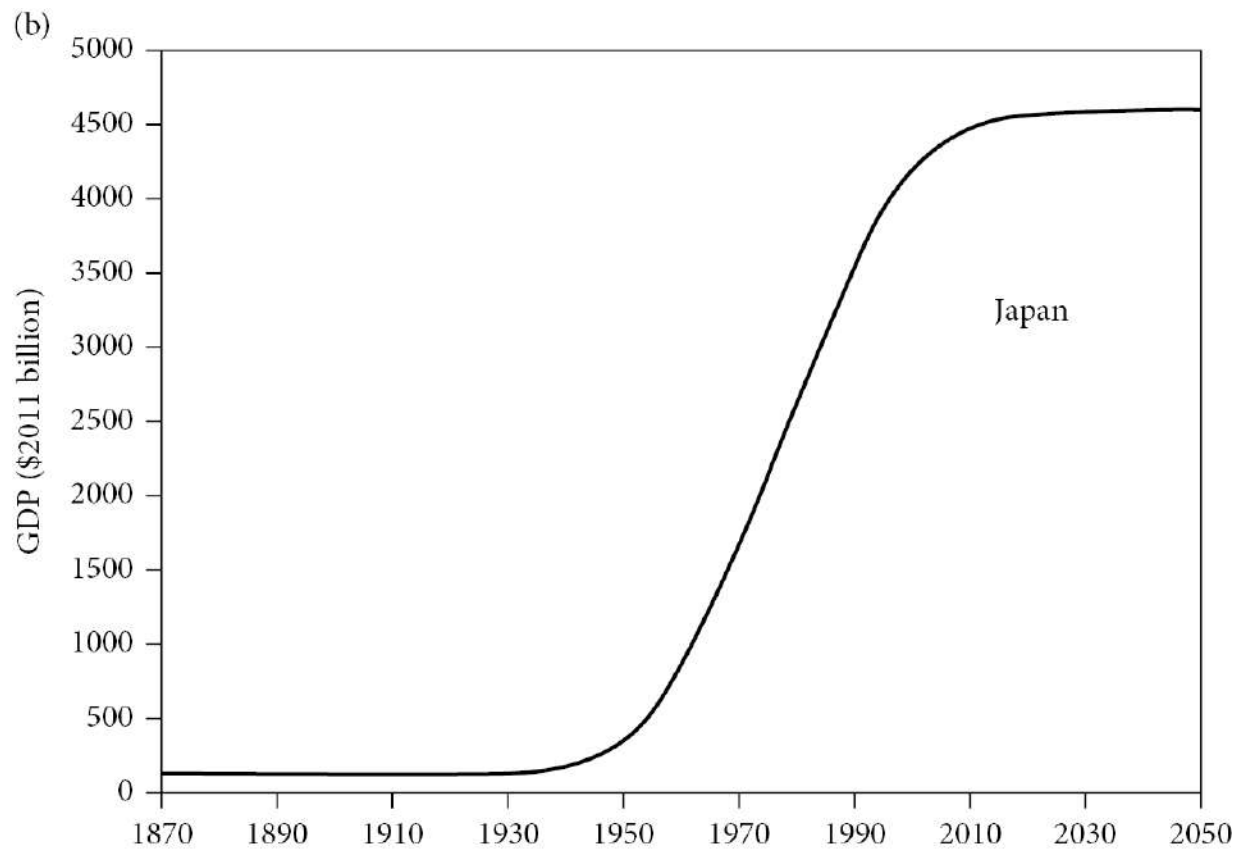
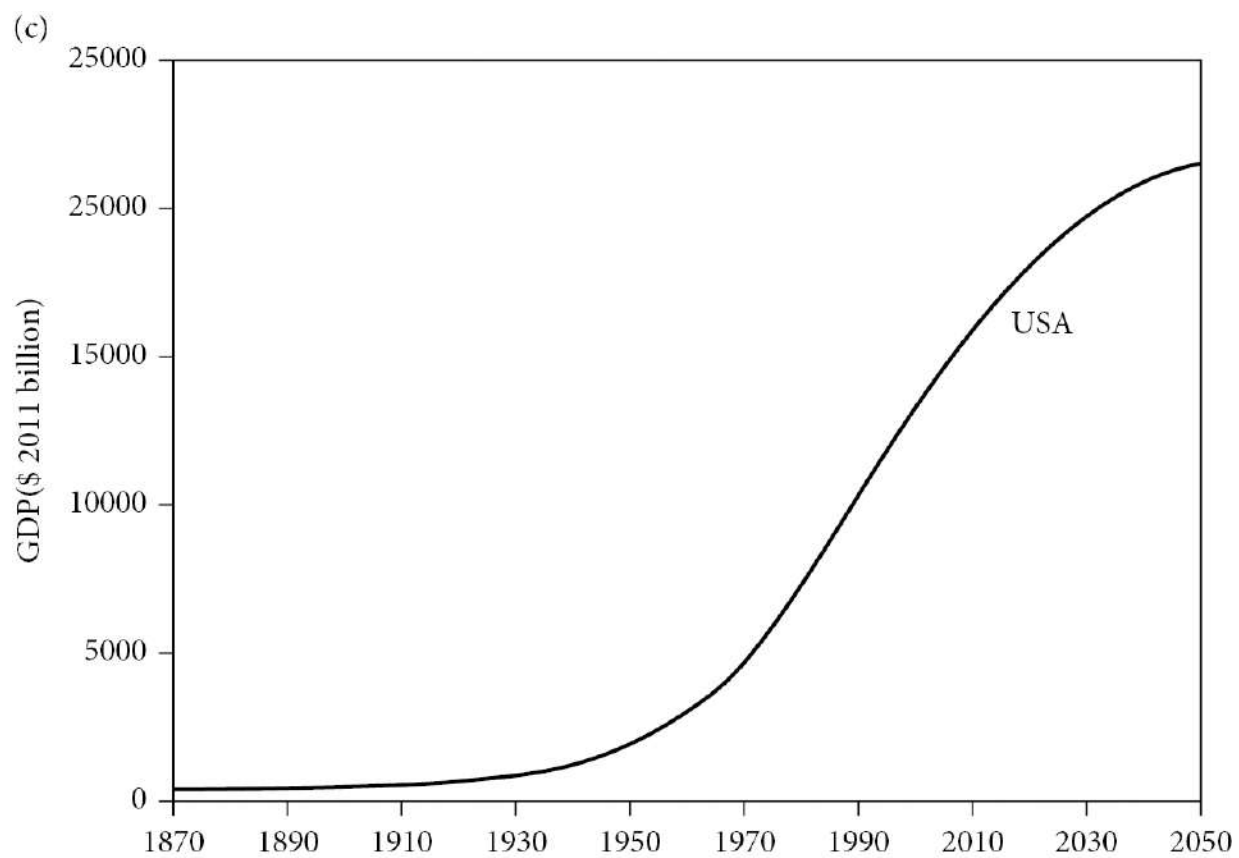
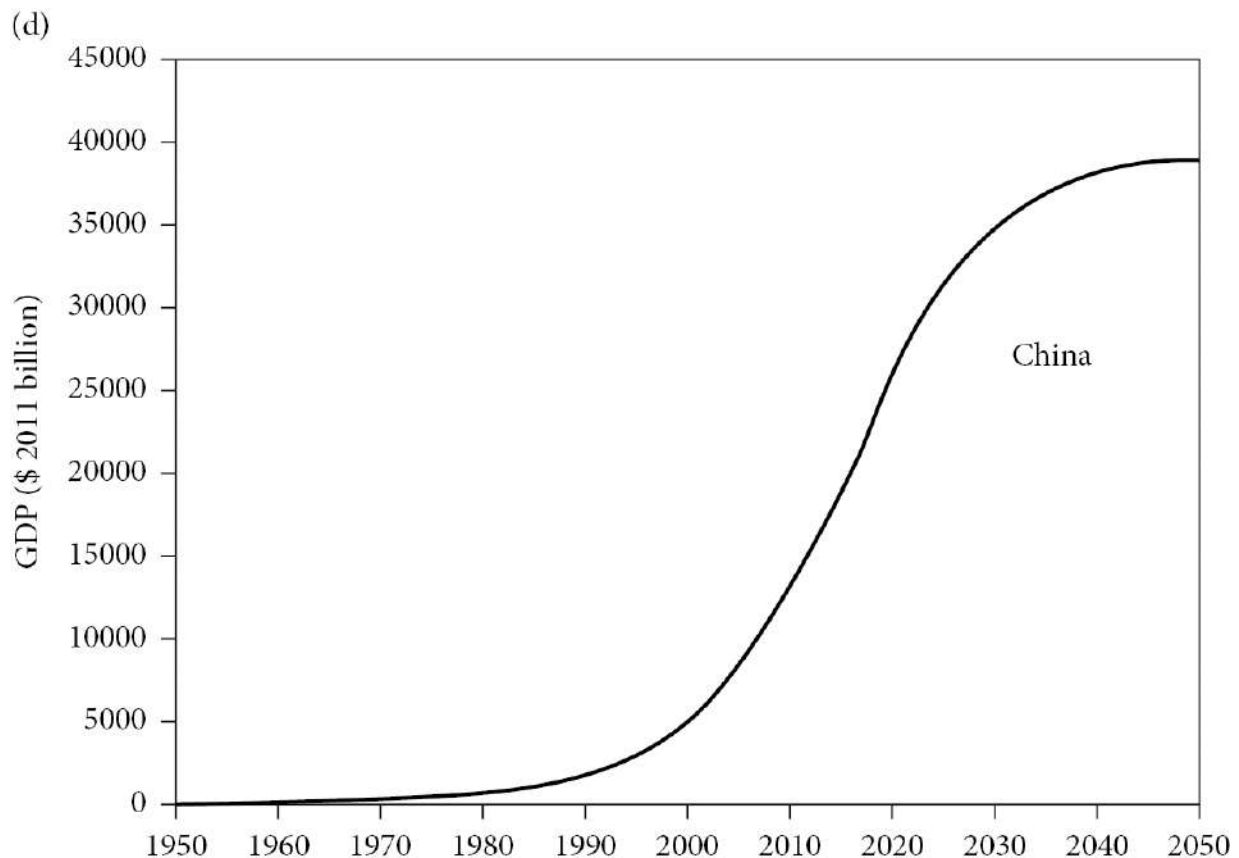


Figure 5.2 a–d Long-term (1870–2015) trajectories and indicated logistic progressions of GDP in France, Japan, the United States, and China. Plotted from data in the [World Bank \(2019\)](#).





Per capita incomes of affluent economies also conform to logistic curves with similarly dated inflection points (Japan in 1982, the United States in 1995) and with limited gains by the mid-21st century. Remarkably, China, although still far from affluent in relative terms, has already joined this group: the inflection year of its average per capita income came in 2012 and the logistic curve indicates an additional 60% gain by 2050 when the country's per capita economic product would be still only a third of the expected US rate. Many Chinese economists are already concerned about this “economic transition syndrome” characterized by a rapid decline in endogenous economic growth that can lead to a vicious cycle of excessive stimulation, rising debt, and further decline of growth followed by additional spending stimulus ([Zhang 2015](#)).

Inevitably, growth of the global economy reflects the slowdown of growth in the United States, China, and Japan, the world's three largest generators of products and services. During the 50 years between 1960 and 2010 the [World Bank \(2019\)](#) data show the decadal maxima of global GDP growth falling from 6.7%/year to 4.4%/year and the corresponding decadal

minima declining from 4.4% to -1.7% /year. These facts confirm that some two-fifths of humanity now live in countries that have either already accomplished their economic transition from very low growth rates to temporarily high gains followed by a more moderate progress, or that have considerably advanced along that trajectory. And while it is unlikely that either India or one of the populous African economies will grow as fast as China has done since 1990, there are strong expectations that the next two generations will see substantial growth in nations that now contain about a third of the global population.

But what lies ahead for mature affluent economies? Will they sustain moderated but still substantial increases for the remainder of the 21st century and beyond? Are they to embark on yet another transition as extended period of low to very low growth lead eventually to stationary economies? Or is their developmental trajectory to shift even more dramatically as they deliberately engineer declining growth rates as the only way to prevent global environmental catastrophes resulting from cumulative anthropogenic assault on the biosphere? Most economists have little doubt believing that growth is an unending process whose rates change, might turn temporarily negative in recurrent economic crises, but in the long run follow an ever-ascending trajectory. For example, an OECD forecast (being just the continuation of an exponential growth of 2.5% a year) has the global economic product rising from about \$76 trillion in 2018 to US\$221 trillion by 2060 ([OECD 2018b](#)).

[Boretos \(2009\)](#) plotted the economic growth of the past two centuries and his logistic curve reached saturation by the beginning of the 22nd century, giving us at least another century of growth. Other results can be obtained by using different starting points and different global estimates of the past economic product. I have plotted the estimates of global economic product between 1800 and 2015; the resulting logistic curve reaches inflection point in the year 2066 and the product saturates at nearly eight times the recent level by 2150. But plotting the estimates and data for half a millennium (1500 to 2015) produced the best logistic fit whose asymptote arrives only around 2500 at the level five orders of magnitude higher than in 2015.

Such curve-fitting exercises are easy to do—and are easy to dismiss. What we know is that, so far, no major economy has seen the absence of growth over an extended period of time—and none has been in a continuous decline. The Japanese economy would have been the likeliest

candidate for this transition. Double-digit annual growth of the 1960s declined to the range of 2%–5% during the 1970s and 1980s, but even as the country’s bubble economy collapsed in 1990 and as the country has experienced more than a generation of unprecedented setbacks (including, since 2010, declining population), its GDP declined in only six of the subsequent 27 years and it managed an average annual growth of 1%, raising the 2019 total (in constant US\$2010) by 30% from about \$4.7 trillion to \$6.21 trillion ([World Bank 2019](#)).

Clearly, even this economic underperformer has come nowhere close to a new stationary economy. For comparison, during the same period (1990–2017) overall GDP gain was 50% in Germany and France and 90% in the United States. America has seen a very strong performance for such a large and mature economy, and the OECD sees the US value rising to about \$39 trillion by 2060, roughly doubling the 2020 total ([OECD 2018b](#)). At the same time, Richard Gordon concluded that the recent technical innovations have not been as consequential as those of the Second industrial revolution (Gordon [2012](#) and [2016](#))—I have made very similar arguments (Smil [2005](#) and [2006](#))—and identified a number of factors (including shifts in population structure, rising inequality, impacts of globalization, and the challenges of energy and the environment) that should reduce long-term economic growth. Not surprisingly, such conclusions are dismissed by the proponents of continuous high growth.

But even a considerable slowdown in the growth of affluent economies would not be decisive globally as the center of growth has shifted to Asia, with China’s total economic output in 2017 being more than 12 times larger than in 1990. And while it is unlikely that India will replicate the Chinese boom (its economy still managed nearly a tenfold rise between 1990 and 2017), its continuous growth and further gains elsewhere in South Asia and in Africa make it obvious that—barring a major collapse induced by a large-scale conflict, a severe pandemic, or a planetary-scale natural catastrophe—the age of relatively high worldwide economic growth is far from over, that there are no endogenous economic forces steering the world to very low growth as a prelude to a new stationary economy. That transition remains beyond the foreseeable horizon.

Forecasting future growth trajectories of the global economy is thus highly uncertain and if we limit the horizon to the next two generations (40–50 years) we may end up with plausible scenarios encompassing a wide

range of outcomes. They include the continuation of recent growth rate (as in the cited OECD forecast), considerably reduced growth (conforming to Gordon's conclusions), fluctuations whose longer-term outcome would be no growth (although even the faltering Japanese economy has not performed so poorly), slow decline, decline that includes sharp downturns with reduced capacity for successful recovery (so far no major economy has experienced that but realistic assumptions can produce this outcome), and rapid retreat and precipitous (perhaps catastrophically induced) collapse. And there is a new consideration in play, the economic response to the threat of excessive global warming.

Structure of Economies

Traditional economies were dominated by subsistence food production: cropping, animal husbandry, or fishing employed the largest share of working population and produced the highest share of the total economic output. Environmental differences resulted in many variations within this universal setup. Societies in densely populated regions with good soils and with abundant precipitation (or with the ability to provide sufficient irrigation) were engaged in intensive farming that included multicropping and complex crop rotations. Aquaculture was a special mode of intensive food production. Societies in more restrictive environments harvested a single staple crop a year and often supplemented its yield by foraging (gathering plants, hunting animals). Other traditional societies practiced shifting cultivation, pure pastoralism, or various forms of agro-pastoral subsistence.

This food provision was accompanied by many other activities that we now categorize as construction, mining, manufacturing, transportation, and services, but the shares of the labor force that were exclusively engaged in these endeavors were low, as many of these tasks were done by peasants themselves, either as required throughout the year or during the slack periods of no fieldwork. An excellent quantitative confirmation of this common reality is provided by the monumental study of China's traditional farming ([Buck 1937](#)). Surveys in 152 localities across China found 68% of all labor engaged only in farm work, nearly 12% only in subsidiary activities, and 20% in a mixture of both, while in the winter wheat-millet

region (where the seasonal pause in field activities left more time for other pursuits) the respective shares were 54%, 23%, and 23%, indicating significant non-farm involvement of rural labor.

Many early modernizers moved from subsistence agriculture to light manufacturing (textile industries based on cotton, wool, or linen), then to expanding extraction of mineral resources and to heavy industry and eventually to much less labor-intensive industrial activities culminating, so far, in microprocessor-based products. During this progression, labor released first by agricultural modernization and later by industrial mechanization finds employment in an ever-widening service sector, first in the combination of retail, education, and public transportation, later in activities ranging from health to financial services and from state-supported scientific research to the mass-scale tourist industry. In contrast, many late starters have moved from traditional agrarian or pastoral/nomadic societies to resource extractors (Iran or Saudi Arabia) or to providers of manufactured goods, often with concentration on particular sectors: post-1950 Taiwan and post-1970 South Korea are perhaps the most successful examples of this rapid shift.

Studies of structural shifts began during the 1930s ([Fisher 1939](#); [Clark 1940](#)) and attracted greater attention after World War II with major (and now considered classic) contributions by Jean Fourastié (1949), Theodore [Schultz \(1953\)](#), Walter [Rostow \(1960\)](#), and Simon [Kuznets \(1966\)](#). Following the structural transition from traditional economies to modern societies is often problematic because reliable data on employment and origins of GDP may be only of recent origin and because many totals are insufficiently subdivided. Most commonly, labor data are available only for broad categories of primary, secondary, and tertiary production.

The three sectors

This division of economic activities was formally introduced by Allan Fisher just before World War II ([Fisher 1939](#)). Although it relies on functionally defined sectors, the division obfuscates as much as it illuminates. The term primary production was introduced in New Zealand in 1891 in order to replace what Fisher called the clumsy category of agricultural and pastoral production used by the country's statistics, and right from its inception the term referred to all harvesting and extractive

endeavors that are pursued by “agricultural, pastoral, mineral and other primary producers” (Fisher 1939, 26).

The category thus combines all forms of food production (fisheries and aquaculture should be also included) with forestry (wood cutting for timber and pulp), and water conservation and supply, as well as with all mining and quarrying activities (fuels, ores, nonmetallic minerals, construction materials) and with their basic processing (sorting of coal before shipping, crushing of construction stone, but not the much more complex crude oil refining). Some of the sector’s products (mostly assorted food items) are sold directly to consumers but most of its output (be it wheat for flour, crude oil for refining, or bauxite for aluminum smelting) becomes the input for the secondary sector.

This combination of forms makes for a rather heterogeneous economic sector whose individual components are often moving in opposite directions during the progress of economic modernization. While employment in farming is steadily (and sometimes rapidly) declining, economic modernization calls for vastly expanded extraction of fossil fuels and minerals, and the displacement of wood by coal eliminates previously intensive tree-cutting activities. Economic development in the United States and Russia/USSR, the two countries with abundant fossil fuel resources, offers two prime examples of these contradictory shifts within the primary production sector. That contradiction is why tracing the development of a narrower category of agricultural output or, more inclusively, the entire food production sector (including animals on pasture, fishing, and aquaculture) is preferable if the requisite information is available.

The original 1921 definition of secondary production included “treatment of raw materials, all manufactures, building and construction of all kinds, and gas, water, and electricity supply” (Fisher 1939, 27). Further definitional finessing and adjustments followed. For example, gas in the original definition refers to gas produced from coal, and this industry was eliminated after World War II by conversion of industries and households to natural gas whose extraction (and field processing) would be a primary economic activity. And in affluent countries many manufactured items common in 1921 (ranging from collar harnesses and horseshoes to manual typewriters, fountain pens, and corrugated metal washboards) no longer exist (except as oddities) in the affluent West. Conversely, there is no shortage of entire industries that did not exist a century ago, ranging from

solid-state electronics (semiconductors, microprocessor, LEDs) to superior construction components (triple-pane windows filled with inert gas; fiberglass insulation; engineered lumber).

The secondary activities are thus also a rather heterogeneous category and wherever more focused data are available I will prefer to follow the shifts in manufacturing, the signature activity of the first phase of economic modernization. Again, this is a super-sector that ranges from the last vestiges of labor-intensive artisanal handwork to completely automated production of microprocessors in multibillion foundries, and whose output includes materials requiring low energy inputs (cut stone, lumber) as well as highly energy intensive products (Al, super-pure Si, Ti, composite fibers)—but it retains the fundamental functional unity of consisting of anthropogenic goods (artifacts).

Fisher's (1939, 32) best definition of the tertiary sector (after noting that it would be a cowardly evasion to define it as everything left over after taking into account all primary and secondary activities) was as the activity “concerned with every new or relatively new type of consumers’ demand.” But the category has evolved to become a real catch-all for what we now call the service economy, and it now includes an ever-growing list starting with such obvious components as government and education, health care, policing, and waste disposal, and including all forms of retail, financial (investment, banking, insurance), legal, real estate, and accounting services; consulting (managerial and technical); and mass media; as well as the entire hospitality sector (from hotels to cruises). The most recent additions encompass diverse services based on the ever-increasing power of microprocessors in mobile devices. But, again, it can be argued that the sector retains its fundamental functional unity by offering anything but tangible goods.

A year after Fisher published his three-sector paper, Colin Clark posited a course of sectoral economic transition (the Clark-Fisher or Fisher-Clark model) with a gradual decrease of employment in primary activities accompanied by a rising share of employment in the secondary sector and, starting a bit later, by a steady increase of tertiary activities (Clark 1940). In some countries the secondary (manufacturing) sector may become briefly the largest contributor before its share begins a gradual decline while the shares of primary and tertiary employment continue their respective

downward and upward trajectories with all modern economies eventually heavily dominated by services.

In 1949 French economist Jean Fourastié published a book about the great hope of the 20th century, in which he quantified the shares of the typical labor force distribution for the three phases of civilization. He also predicted that the transition to the tertiary sector should eliminate unemployment because of the sector's essentially unlimited size (Fourastié 1949). According to Fourastié, in traditional societies (such as those of medieval Europe or, at the time of his writing, of economically undeveloped countries of Africa and Asia) the primary sector employs 70% of all labor, the secondary one accounts for 20%, and the tertiary sector amounts to just 10%.

During the transitional period, the workforce in the primary sector is reduced to 20% of the total, the secondary sector (whose expansion is driven by higher energy use and widespread mechanization) dominates with 50%, and tertiary employment rises to 30%. Finally, in the tertiary civilization (that is, in modern affluent societies), employment in the primary sector is no larger than 10%, the secondary sector employs 20%, and the tertiary sector dominates with 70% of all workers. And the growing size and diversification of the tertiary sector has led to the creation of two additional categories, with the quaternary sector including all information management and the quinary sector subsuming all knowledge-based activities.

As with any generalized model, Fourastié's phases do not reflect many specific realities. US data on the distribution of employment by major sector have been available since 1850, when the primary sector dominated but the labor force was equally split between the secondary and tertiary sectors, and the latest available division shows the primary sector at just 2% (rather than at 10%), the secondary sector at less than 13%, and the tertiary one as just over 80% ([Urquhart 1984](#); BLS 2018). This finding means that the retreat of the US primary sector as well as later deindustrialization proceeded much further than Fourastié posited, and that the tertiary sector is even more dominant than indicated by his projections.

The Chinese trajectory demonstrates an even more significant departure from a generic model. Republican China remained overwhelmingly agrarian (the primary sector declining from 83% to 79% of all employment between 1915 and 1933) and in 1952, three years after the Communist took

power, the respective shares of the three sectors had shares of 75%, 10%, and 15% (Wu 2016). Despite nearly three decades of Maoist industrialization, China's employment by sector reached Fourastié's first phase only in 1978 (shares of 71%, 17%, and 12% being very close to the model's 70%, 20%, and 10%), the year at whose end the post-Mao economic reforms were first announced. And then, despite the four decades of rapid economic growth and despite China's emergence as the world's largest producer and exporter of manufactured goods, by 2016 the employment shares in the three sectors (at 28%, 29%, and 44%) were not close either to the second or the third stage of development, with still too many people in the primary sector and too few in the other two sectors (NBSC 2018).

From farms to factories

Industrialization had two great physical enablers. First, large numbers of city-bound migrants released from the countryside by gradual modernization of traditional farming made it possible to operate often highly labor-intensive tasks of material processing and only partially mechanized manufacturing. In the common (albeit misleading) terminology, no industrial revolution could have taken place without the preceding agricultural revolution. This labor push factor was potentiated by the effect of the already noted Engel's law: reduced share of spending on food can be used to buy more manufactured products. Second, new opportunities in industrial production—enabled by technical advances and energized by the supply of inexpensive fuels and electricity—created a powerful labor pull factor.

Alvarez-Cuadrado and Poschke (2009) investigated the relative importance of these push and pull factors by examining 19th-century data on relative prices and on agricultural employment for 12 countries, including the United States since 1800. Their conclusion was that the pull effect dominated until about World War II and the push factor became more important afterwards, a trend that means that the pull effect is more prominent in economies in early stages of their structural transformation. As expected, these structural shifts were also subject to various nation- and region-specific circumstances. The pull effect of America's post-1865 industrialization was so strong that it extended to nearly all European

countries, not just to the continent's most impoverished regions. Coal was commonly the dominant energizer of the first structural shift but in some regions the initial stages of industrialization depended heavily on fuelwood or on water power ([Smil 2017a](#)).

But to see industrialization as just a period of an unprecedented one-time shift of labor from villages to cities would be to ignore the complex dynamics of the process. We could cite indicators showing that in all affluent countries the process of industrialization has ended some time ago—or use other indicators to prove that it continues as the sector keeps adjusting to new economic circumstances: changes in the composition of industrial output and changes in production techniques and sources of supply for major commodities have been as important and no less marked than the change in the pattern of the overall output ([Chenery 1960](#)).

The first, compositional shift has been from pioneering textile and metallurgical activities (the latter sector was indispensable in order to meet new infrastructural needs, starting with the expansion of railways) toward mass-scale production of consumer goods and, most recently, toward meeting unprecedented global demand for new electronic devices. The second shift, in production techniques and in the sourcing of materials, has been perhaps the most fundamental driver of technical innovation that has led to higher productivities, low cost, and much improved performances, be they measured in terms of efficiency or reliability and durability.

Aircraft production is a perfect illustration of these continuing changes. The sector did not even exist during the 19th century, and the first-generation airplanes built between 1903 and 1914 had few metallic parts besides their reciprocating engines: wood, fabrics, and waxed twine were essential ([Mraz 2003](#)). During the 1920s came monocoque construction, using first plywood and then aluminum for aircraft bodies and interiors. Aluminum fuselages, wings, and rudders dominated until the first decade of the 21st century; starting in the 1950s, lighter plastics took over the planes' interiors. Composite materials, consisting of matrix or reinforced resins and superior at handling tension, are now the preferred choice for fuselage and wings. In 2011 Boeing 787 became the first jetliner with carbon-fiber-reinforced polymer. Steel makes only 10% of the plane (mostly in the landing gear) and aluminum 20%, but composites are 50% of its mass ([Hale 2006](#)).

Manufacturing methods began with artisanal products made by individuals or families and often progressed from small workshops to large factories. This sequence, typical of weaving and sewing, was repeated with car making (the first small workshops were often run by bicycle mechanics) as well as with aircraft construction. Even the engine of the world's first successful airplane flown by Orville Wright in December 1903 was custom made (without any drawings!) by Charles Taylor, whom the Wright brothers employed as their mechanic ([McDaniel 2018](#)). World War I demand led to serial production, and between 1917 and 1919 US factories made just over 20,000 Liberty engines that were widely deployed during the 1920s. Mass-scale production of propeller-driven aluminum-fuselage planes reached impressive new highs during World War II, when US factories turned out 295,959 airplanes, compared to 117,479 made in the United Kingdom, 111,787 in Germany, and 68,057 in Japan ([Smil 2013c](#)).

With the introduction of much larger and far more complex jetliners relying on electronic (fly-by-wire) controls, aircraft manufacturing had to become a superbly orchestrated assembly of parts from scores of suppliers in more than a dozen countries. Leaving bolts and rivets aside, Boeing's smallest plane (737) is assembled from about 400,000 parts, while the latest Boeing 787 has 2.3 million parts ([Boeing 2013](#)). With the use of these components, delivered just in time, it takes just nine days to build Boeing's bestselling 737 in the company's Renton, Washington facility. And similar transformative trajectories could be outlined for the manufacturing of motor vehicles or electronic components. In the first case the transformation runs, again, from artisanal vehicles built in small workshops (often by former bicycle mechanics) to highly automated factories whose global annual output is now approaching 100 million units (OICA 2019).

In the second case the manufacturing changes have been so profound that "incredible" might be the most fitting adjective to describe the advances, from bulky and unreliable hot-glass vacuum tubes to ever-smaller solid-state electronic devices that are now indispensable to operate an ever-increasing number of large and small products. These realities remind us that industrialization has been a multifaceted, multistage evolving process whose achievements cannot be judged simply by such aggregate indicators as total employment or a share of GDP.

The industrial sector has combined some notable cases of technical inertia with continuous technical innovation. Its development has proceeded

in both quantitative and qualitative terms, the first trend leading to mass-scale production (and hence economies of scale and more affordable products) in virtually every consumer category (from motor vehicles, globally now close to 100 million units a year, to mobile phones, globally now close to two billion units a year), while the second trend has produced items of improved functionality, durability, and reliability (a well-maintained jetliner can operate for 25 years and log well over 50,000 hours of flying time) and often also of a greater esthetic appeal.

For many countries historical data and modern statistics on employment are available for more disaggregated categories of agriculture (sometimes combined with fishing and forestry), extractive industries, manufacturing, construction, commerce and finance, transportation and communications, and other services ([Mitchell 2007](#); USBC 1975; NBSC 2018; SB 2017). I will use these divisions to trace the trajectories of sectoral economic transitions by focusing on the retreat of food production and the rise of manufacturing and services in a few major countries and, in closing, noting also the recent global trends.

Once again, the economy of England (and of the United Kingdom since the Acts of Union of 1707) was in the lead: it was already relatively diversified (mining, commerce, sailing) in the late Middle Ages and it became, at least as far as the sectoral origins of GDP go, predominantly non-agricultural well before the beginning of the early modern era. Reconstructions by [Broadberry et al. \(2015\)](#) show agriculture contributing about 42% of the total economic product in 1381, then little change during the next 200 years before the share declined to 28% by 1700 and to 22% in 1841. In terms of employment, reconstructions by the [Cambridge Group for the History of Population and Social Structure \(2019\)](#) show the male labor force in agriculture declining from about 75% in 1400 to 40% by 1750 and 15% by 1875. That trend made the country a distinct outlier, as the structural transition was far less advanced anywhere else, with the 1870 farming labor force at around 50% in the United States, Germany, and France and surpassing 60% in Japan.

US data on the distribution of the labor force have been available since the beginning of the 19th century, when the country was an overwhelmingly agrarian society: in 1800 about 83% of all labor force was on farms, and manufacturing, trade and transport, and domestic services each accounted for about 3% of the total ([Lebergott 1966](#)). By 1850 the labor force on

farms was down to 55% of the total but the relative decline during the second half of the 19th century was slowed down by large-scale expansion of a westward-moving wave of new farms set up by immigrants on the Great Plains (Fite 1977). Dempster and Isaacs (2014) showed how the Civil War drove industrial expansion as it created a fundamental structural shift in the relationship between labor and its sources of employment: without the war the structural shift would have been slower.

By 1900 41% of the country's labor force was still on farms but the share was nearly halved by 1930, when agriculture accounted for almost 8% of the US GDP (Dimitri et al. 2005). At the end of World War II, the two shares were, respectively, 16% and nearly 7%, and by the year 2000 they shrank to just 1.9% and 0.7%. But this great retreat was accompanied by impressively increasing economies of scale. As already noted, the number of American farms was more than halved during the 20th century; their average size as well as their productivity had more than doubled and farm exports expanded eightfold. Increased specialization was another factor behind the rise in productivity: during the 20th century the average number of commodities produced per farm declined by about two-thirds.

In the early stages of economic modernization most of the labor released from villages ended up in manufacturing and (in countries endowed with plenty of coal and ores) also in mining and other extractive industries. Again, the pioneering England was an early major exception. Between 1600 and 1841, the year when reliable employment data begin, contributions of the industrial sector to England (and the United Kingdom's) economic product remained both high and remarkably steady at about 36% (Broadberry et al. 2015). Contrary to a common impression, the pace of British industrialization quickened only during the 1850s. According to the 1851 census Britain still had many more traditional craftsmen than machine-operating factory workers, more shoemakers than coal miners, and more blacksmiths than ironworkers (Cameron 1985).

British manufacturing reached the peak of its global primacy during the mid-1880s when the country produced 43% of the world's manufactured exports, compared to 6% in the United States and 16% in Germany (Matthews et al. 1982). Manufacturing became both the foundation and the most impressive sign of the country's economic leadership as the British engineers and entrepreneurs pioneered innovations ranging from subways to bicycles and ocean liners and from affordable steel to steam turbines and

pneumatic tires ([Smil 2005](#)). The sector remained quite strong during the first six decades of the 20th century, it made fundamental contributions to the British victory in two world wars, and it helped to launch such advances as synthetic materials, jetliners, and electronic computing. Manufacturing's share of the British labor force remained remarkably steady, barely shifting from 38% in 1901 to 37.4% in 1961, when the sector employed the record number of nearly nine million workers. That was the time the Concorde project, a paragon of high-tech innovation, had officially begun (in 1962) and when British Steel and Rolls Royce were globally recognized marks of quality.

Post-1850 expansion of manufacturing was obviously a key factor in creating and consolidating modern high-income economies, and many studies have shown the sector's unmatched benefits ([Duesterberg and Preeg 2003](#); [Smil 2013c](#); [Cantore et al. 2017](#)). Perhaps most importantly, manufacturing accounts for the largest share of innovation in modern societies with about two-thirds of all R&D (research and development) originating in the sector. Manufacturing activities generate numerous backward and forward linkages that create both traditional jobs (logistics, accounting) and new employment opportunities (online sales, global marketing) and that require integrating material handling, transportation, and sales with the requisite education, training (apprenticeship programs being especially important in providing skilled labor), and incessant innovation required to stay competitive in the global market. All of this means that manufacturing beats services in generating additional value throughout the economy.

And manufacturing has been a long-lasting source of economic growth, with structural transformation within the sector (increase of value added) being the more important reason of this stimulus than the scale of manufacturing employment ([Cantore et al. 2017](#)). Manufacturing is also a leading provider of well-paying jobs and the leading source of traded goods. The latter reality is particularly important in a global economy, in which nations with a strong competitive traded sector have a great advantage ([Atkinson et al. 2012](#); [Smil 2013c](#)). Obviously, it is no coincidence that countries with relatively high shares of export-oriented manufacturing (Germany, the Czech Republic, South Korea, Japan) have substantial trade surpluses as well as the world's lowest unemployment rates ([World Bank 2019](#)). That combination of factors is why the post-1980

decline of manufacturing jobs, clearly evident in all but a few affluent countries, has been a matter of public and political concern.

The retreat has been particularly rapid in the country that pioneered the sector's rise. The United Kingdom had a long-standing trade deficit in basic materials, but for more than a century it had a significant surplus in semi-manufactured and finished products; the latter balance turned negative in 1983 and subsequently those deficits have only deepened as the British deindustrialization accelerated (Kitson and Mitchie 2014). Jobs in manufacturing declined to fewer than 5 million by the year 2000, the sector's share of labor force fell to less than 9%, and value added in manufacturing slid below 20% by the late 1980s and reached the record low of 8.7% in 2009, followed by a marginal recovery to 9.2% by 2017 ([World Bank 2019](#)). Reasons for this retreat include rising competition (first from the United States, after 1970 increasingly from Asian manufacturers), the loss of the empire, the intransigence of heavily unionized labor, frequent crippling strikes, faltering innovation, and a recurrently high value of the currency.

With only 9% of its labor in manufacturing, Britain, the pioneer of factory-based modernization, has become the world's most deindustrialized major economy. Other affluent countries have traveled along similar trajectories as their shares of GDP value added by manufacturing have declined well below 20%: in 2017 they ranged from 18% for Switzerland to 10% for France (the EU mean was 14%), with Germany (21%), the Czech Republic (24%), and South Korea (28%) being the three exceptions ([World Bank 2019](#)). The US share is now less than 12%; the Canadian contribution is nearly as low as in the United Kingdom. Job losses have been severe. The US manufacturing employment peaked in September 1979 with 19.6 million jobs, it declined to 17 million by the end of the year 2000, and then (as China joined the World Trade Organization and the surge of cheap imports flooded the United States) it fell to the record low of 11.4 million by March 2010, followed by a partial recovery to 12.8 million by the end of 2019 (FRED 2019).

Even after this recovery the net post-1979 loss of nearly seven million (35%) of manufacturing jobs continues to have many economic and social repercussions, particularly in Pennsylvania, Ohio, Michigan, and Wisconsin, the states that were disproportionately affected. And the impact has been even greater in smaller one-industry towns that had lost their long-

established economic base as generations worked in textile, apparel, furniture, household goods, or appliance factories. At the same time, neither the declining employment in manufacturing nor the sector's decreasing share of GDP has been translated into an absolute decline of factory production.

Thanks to its rising productivity, US manufacturing had continued to add more real-term value almost every year until the year 2000, after a brief mild dip it reached a new record in 2007 but by mid-2009, during the greatest post-WWII economic downturn, it retreated by some 12%. However, by 2018 the subsequent, nearly steady rise brought it close to the 2007 record (FRED 2018). The sector still offers some of the best-paying jobs, especially for duties not requiring post-secondary education, and it remains a leading source of technical innovation, with some US products—ranging from GE's jet engines and Caterpillar's heavy machinery to Intel's semiconductors and Pfizer's pharmaceuticals—still occupying the highest grounds of global quality, reliability, and durability.

Further manufacturing declines are likely, but it appears that in most of the high-income economies the period of the most rapid deindustrialization has largely run its course. In contrast, in 2017 China, now the largest manufacturing economy, derived 29% of its GDP from the sector, a slight decline from the 2006 high of 32.5% ([World Bank 2019](#)). But when we look beyond the standard sectoral categories, we quickly discover that tracing the rise and retreat of manufacturing is not as simple as comparing statistics on labor force or on origins of GDP. Definitional boundaries are an obvious problem.

According to the US Census Bureau the sector includes “establishments engaged in the mechanical, physical, or chemical transformation of materials, substances, or components into new products. The assembling of component parts of manufactured products is considered manufacturing, except in cases where the activity is appropriately classified in Sector 23, Construction” (USCB 2018). This definition means that “establishments that transform materials or substances into new products by hand or in the worker's home and those engaged in selling to the general public products made on the same premises from which they are sold, such as bakeries, candy stores, and custom tailors, may also be included in this sector.”

But when people think about modern manufacturing, they envisage mass-scale, highly mechanized assembly of cars or mobile phones, not local

bakeries or custom tailors. When French commentators are concerned about the loss of manufacturing jobs, they do not have the frequent closure of neighborhood *boulangeries* in mind! And defining “new products” within the manufacturing category cannot be done unambiguously. According to the US categorization, ready-mixed concrete and electroplating of metals count as parts of manufacturing but beneficiation of ores is a part of mining and “publishing and printing” are part of the information sector: a book is obviously a manufactured artifact but because its value “to the consumer lies in the information content, not in the format” (USCB 2018) it gets excluded.

And a much more fundamental problem is the changing nature of modern manufacturing, as the sector depends on astute management; on just-in-time deliveries of parts and components coming in by trucks, ships, and airplanes; on efficient payroll and accounting; and, above all, on R&D activities that are necessary to update and to improve established designs and to introduce entirely new products in order to remain competitive in the global market. Not surprisingly, one international comparison found that services purchased from other companies’ sectors other than manufacturing comprised 30% of the value added to products made in the United States and 23–29% of goods from major EU economies; another one showed that service-related tasks added up to 53% of US manufacturing jobs with analogical shares at 44%–50% in large EU countries and 32% in Japan ([Levinson 2012](#)).

In the United States such services are considered to be a part of manufacturing only when provided internally—but not when they are (as is now commonly done with tasks ranging from payroll to design and from contract research to marketing) outsourced. Because of these realities it is quite clear that a different accounting and classification framework might result in substantially different shares of jobs that are (directly, and indirectly) associated with modern manufacturing, and that the degree of deindustrialization has not been as far reaching as indicated by commonly used indicators. At the same time, different accounts could also show that agricultural sector has declined much less than shown by employment shares in cropping, animal husbandry, and aquaculture.

Again, the difference lies in the changing nature of modern farming. Traditional farming required very few external inputs: a portion of harvested seeds was set aside for the next year’s planting, many simple

tools were made by farmers themselves or by village craftsmen, and subsistence food production left only small shares of harvests for sales outside of villages and nearby towns. But setting the limits of modern agricultures in fields and barns is arbitrarily misleading, as food production is now utterly dependent on large-scale external inputs, with seeds, materials, artifacts, machines, and know-how coming not only from different parts of a country but also from abroad.

Seeds do not come from the previous crop but are products of decades of intensive research and commercialization by specialized seed companies. Profitable harvests require adequate applications of agrochemicals (fertilizers, herbicides, insecticides, fungicides); fieldwork and irrigation are now inconceivable without efficient machines energized by liquid fuels and electricity. And food distribution is now in many respects global. Moreover, subsistence agricultures produced all but a small share of all food for direct consumption by rural families, while in modern, highly urbanized societies farmers produce for distant markets. As a result, they deploy complex systems of food storage, processing, and distribution without which their products would never reach the consumers who would not be able to consume most of it without another elaborate system of retail and household preparation and who now consume a significant share of their meals outside their homes.

All of this makes a compelling case for redefining the boundaries of a modern food production system. Comparison of direct and indirect energy uses in modern food systems indicates to what extent such a redefinition could change our perception of a retreating agricultural sector. While the national shares of direct energy use in food production (crop cultivation and animal husbandry) are on the order of 2–4% of total primary energy supply, national food systems claim on the order of 15% of all primary energy ([Smil 2008b](#)). Counting only those services that directly contribute to harvests and their distribution would result in a smaller multiple, but it appears quite plausible that a redefinition of food production boundaries may see 5–8% of all jobs and of national GDPs in the sector.

In any case, the historical record makes it clear that the transition from overwhelmingly or largely agrarian societies to economies where manufacturing is the sector responsible for the largest share of GDP has been a nearly universal pattern pioneered by the United Kingdom and followed first (during the latter half of the 19th century) by the countries of

Western Europe and North America, then replicated by Japan and the USSR, and followed by waves of post-1950 industrialization in Latin America and Asia, with Taiwan, South Korea, China, and Vietnam being the latest prominent late starters.

In the United Kingdom more people worked in manufacturing than in agriculture (and fishing and forestry) already by the 1830s and by 1880 the difference was twofold ([Mitchell 2007](#)). In the United States the two sectors employed the same share of people by 1910 and by 1950 producing goods provided jobs to three times as many Americans as securing food ([Urquhart 1984](#)). And, to give just two more examples of now affluent economies, in the Netherlands there were more jobs in manufacturing than farming and fishing only since the time of World War I, and France had more farmers and fishers than factory and artisanal workers until the early 1950s ([Mitchell 2007](#)). In contrast, in China the crossover year for the total employment in primary and secondary activities came only in 2014, and in India there are still about twice as many people producing food than making goods.

At the same time, manufacturing's role has already weakened in many developing countries, with some of them even experiencing premature deindustrialization. [Timmer et al. \(2014\)](#) looked at the post-1950 data of value added and people employed in ten broad sectors for more than 30 countries in Asia, Latin America, and sub-Saharan Africa and found that early post-WWII expansion of manufacturing, related to a growth-enhancing reallocation of resources, had stalled in many African and Latin American economies during the mid-1970s and 1980s. When their growth rebounded in the 1990s, the labor force moved mainly to services (led by retail and distribution), a shift that made those countries fall behind the world innovation frontier. This analysis was confirmed by re-examination of a larger set of developing countries, a study that showed that between 1950 and 2005 the sector's expansion was only moderately associated with overall economic growth and that since 1990 it has become a more difficult route to growth than in the previous decades.

This premature deindustrialization has not been due to any changes in the sector's development potential but it has been a consequence of a rapid shift of manufacturing to a small number of countries, most obviously to China and South Korea and, for specific industries, including apparel and electronics, also to Vietnam, Pakistan, Indonesia, or Bangladesh ([Haraguchi](#)

et al. 2016). This shift also means that, contrary to a common perception, the manufacturing's share of global employment did not fall between 1970 and 2010: rapid within-country manufacturing productivity growth that lowers national manufacturing employment shares in advanced economies was counterbalanced by increased manufacturing jobs in lower-productivity economies (Felipe and Mehta 2016).

From factories to services

Allan Fisher, in his pioneering paper on three economic sectors, includes “the whole of the transport and communication, and commerce and finance groups, as well as professional workers, and those engaged in public administration, entertainment and sport, or personal and domestic services” in the last category (Fisher 1939, 36). This broad scope endures: the US Bureau of Labor Statistics defines “service-providing industries” as a super-sector group that includes trade, transportation, and utilities (including wholesale, retail, and warehousing); information; financial activities (including insurance, real estate, and leasing); professional and business services (ranging from scientific and technical to waste management); education and health services; leisure and hospitality (including arts and entertainment); other services; and government (USDOL 2019).

Given the history of rising agricultural and manufacturing productivities, it was inevitable that most people in modern societies will end up doing something other than growing food and making things. Moreover, the broadly defined service sector includes activities that have not fundamentally changed for generations (from pre-school education to household repair trades to playing professional sports) as well as those that have undergone changes as profound, or even greater, than some of the great manufacturing transformations I noted in the preceding section. And there are also entirely new occupations that did not exist even a generation ago.

These transformed and brand-new services have created unprecedented opportunities to employ people in activities that might be classed as a part of a new information sector and that consist of one or more of the following information-centered activities: collection (texts, data, images, multimedia), classification, aggregation, analysis, evaluation (generic and customized), transmission, and storage, all done in order to gain superior insights (be it

into consumers' decision-making or into an adversary's thinking), to increase sales, and to optimize (or to maximize) direct and indirect corporate, political, or policing control (ranging from research on opposition parties, industrial espionage, and electronic hacking to dense networks of closed-circuit TV cameras and to China's social credit monitoring).

In some major economies, the employment shift to services can be traced from the mid-19th century—in 1849 services employed 27% of the Dutch labor force; in 1850 the share was 14% in Denmark ([Mitchell 2007](#))—but for most countries reliable data series began only during the 20th century. In 1900 the French share was 23%; in 1915 China's share was about 14% ([Wu 2016](#)). This difference reflects the respective stages of economic transition but the statistics show an important commonality. Because of traditionally disproportionate shares of females in many service sectors, there has been a very long gap (decades, often more than a century) between the time when more women began to work in services than in manufacturing and when the same transition affected men ([Figure 5.3](#)).





Figure 5.3 Morning in a Parisian railway station in early 1914 as office workers and shop assistants arrive for work. From *The Illustrated London News*, April 11, 1914.

In the United Kingdom women employed in services had greatly outnumbered those in agriculture and fishing for most of the early modern era and more women have worked in services than in manufacturing since 1860. But the total of British men in services had surpassed the total in farming only during the second decade of the 20th century, and only during the first decade of the 21st century did the number of men in services top the total in manufacturing ([Mitchell 2007](#)). Similarly, in the Netherlands more women have worked in services than on farms at least since the early 1850s but for men the switch came only in 1960, and the respective switch years in Belgium were 1961 for women and 2003 for men ([Mitchell 2007](#)).

In the United States the shares of employment in goods-producing and service sectors were almost identical in 1850 (at, respectively, 17.7% and 17.8%) and then grew in tandem during the second half of the 19th century reaching, respectively, 30.5% and 31.4% by 1900. Afterwards manufacturing's share grew only marginally: by the time of its peak at about 35% in 1952 services had a 53% share of the total and by 2016 they reached 80.3% ([BLS 2018](#)). At that level the future share will change very little, with the Bureau of Labor Statistics forecasting 81% in 2026. Intrasectoral shifts within this heterogeneous category have been as remarkable as its overall increase and they include both expected and surprising trends.

Unfortunately, some long-term comparisons of transitions within the service sector are not possible, because of the problems with definitions and inconsistent categories. For example, the US data on domestic workers show that their share of total labor force had nearly quadrupled from 2.1% in 1800 to 7.7% by 1870 before declining to 3.4% by 1960 ([Lebergott 1966](#))—but the US labor statistics do not recognize this category anymore even though in 2012 the country had 2 million in-home workers, more than 90% female and disproportionately immigrants ([Shierholz 2013](#)). Instead, the *Monthly Labor Review* lists employment in personal service (1.4 million

in 2015), a category unhelpfully described as “personal and laundry services.”

More importantly, the early-20th-century US data combine jobs in the health sector with those in information, professional, and business service and with social assistance in the category of “other professional services.” In 1910 this heterogeneous category employed only 3% of the non-farm labor force, but by the year 2000 healthcare and social assistance jobs reached 11 million and in 2018 they surpassed 19 million, or 12.2% of all labor force, and the education-health super-sector employed nearly 24 million people, or nearly 15% of working Americans ([BLS 2018](#)). Remarkably, the ratio of physicians per 100,000 Americans has changed much less than people might think: from 170 in 1850 to 258 in the year 2000, roughly a 50% increase in 150 years (USBC 1975; [World Bank 2019](#)).

Most people think that government bureaucracies have grown uncontrollably but the historical comparison shows that it could have been worse. In 1900 7.2% of the US non-farm labor force worked for government (federal, state, and local), by 1950 that share was 13.3%, and by 2016 it rose only marginally to 14.2% ([BLS 2018](#)). The relative doubling in 116 years does not seem to be so excessive when one considers the post-1900 emergence and growth of the welfare state and the multiplication of government regulation that has resulted in unprecedented federal, state, and local intervention and oversight in myriads of everyday affairs. Perhaps an even more counterintuitive shift has affected transportation and public utilities.

In 1910 the Ford Model T was just two years old—by 2016 America had nearly 270 million motor vehicles; in 1910 electrification was still in its early stages—now it is universal, as is natural gas heating in colder parts of the country. But in 1910 the country still had about 1 million horses in its cities and towns, railroads were close to the peak of their importance, and coal gas was widely used for lighting in cities. Displacing horses and trains by private cars (and later by airplanes) and replacing coal gas by centrally generated electricity and by piped natural gas had greatly reduced the total employment in transportation and public utilities, from 12.6% of non-farm labor in 1910 to just 3.8% in 2015. Even more remarkably, the sector’s total 2015 labor force of 5.4 million people was just 68% larger than in 1910—although in the intervening 107 years the country’s population had more

than tripled (from 92.2 to 309.3 million) and personal mobility increased by an order of magnitude!

Economies of scale—from the demise of neighborhood stores and rise of supermarkets and shopping malls to the recent mass-scale embrace of online orders—had actually cut the share of employment in trade (wholesale and retail) from 16.5% in 1900 to 13% in 2018 even as the total spending rose about 50-fold (USBL 2006; USDL 2019). The share of financial services (including insurance and real estate) has more than doubled, from just 2% of non-farm labor in 1900 to 5.3% in 2016. In 1910 about 900,000 people (3.5% of non-farm labor) were employed in education; by 2015 the total rose to nearly 14 million and it had nearly tripled in relative terms to 9.7%.

International comparisons are often thwarted by incompatible categories, but the sectors that are readily comparable show both the expected convergence toward similar service rates and the persistence of national peculiarities. Not surprisingly, China's continuing construction boom means that about 15% of urban labor force was employed in the sector in 2016, compared to 7.7% in Japan and only 4.3% in the United States. Labor shares in transportation (at, respectively, 4.7%, 5.2%, and 3.2%) show convergence but China's health sector is still weak (4.8% of urban labor in 2016, compared to 12.5% of all labor in Japan and 12.2% in the United States [[World Bank 2019](#)]).

Worldwide data for the entire service sector, modeled by the International Labor Organization, have been available since 1991 and their 2017 extremes range from 7% in Malawi to 84% in Singapore, with means of 31% for sub-Saharan Africa, 72% for the European Union, and 51% globally ([World Bank 2019](#)). Obviously, the transition to services has been essentially completed in all affluent countries, where the 2017 extremes for major economies were 71% in Germany (because of the country's still strong manufacturing sector) and 81% for the United Kingdom (reflecting the already noted deindustrialization). Brazil (69% in 2017) is almost there, China (56%) still faces at least a decade of further structural change, India remains far behind with 33%, and the shares of people in services in South Sudan or Niger are lower than were the shares in some Western European countries during the late 19th century!

Heterogeneity of the service category makes it difficult to offer general conclusions about the consequences and the desirability of the transition

judged by the prospects of income, benefits, job longevity, and personal satisfaction. For example, in some instance the structural shift was not the engine of growth. Decomposition of income changes into labor productivity within sectors and changes in the intensity of employment participation suggested that the labor productivity growth, rather than shifts in employment across sectors, was the leading source of per capita GDP gains in most Asian economies ([Foster-McGregor and Verspagen 2016](#)).

Transition to services has also had a complex effect on employment and income equality. The service sector did not gain all of its jobs simply as transfers from agriculture, other primary activities, and manufacturing: its employment growth originated largely from the expansion of the labor force, above all from the increased participation of women ([Urquhart 1984](#)). Going beyond the traditional employment as domestics, these new opportunities were initially concentrated in education, health, and hospitality sectors but they have eventually expanded to finances, advertisement, information, and management.

Expansion of service economy should lead to further growth of manufacturing but this link has been of marginal importance in many affluent economies in which the new demand from goods was supplied by inexpensive imported products. In North America and in many European countries the large-scale transition to services has been accompanied by often rapid deindustrialization and this combination has made it particularly difficult to accommodate males without higher education. As a result, during the two recent periods of the highest unemployment (in 1982 and in 2009), the rates for men were up to 22% higher than for women ([FRED 2018](#)).

Moreover, the shift to services—with many low-paying and many part-time jobs in retail and hospitality sectors—and losses of well-paying manufacturing jobs have contributed to rising economic inequality. Causes and consequence of this shift have been widely analyzed and debated ([Milanovic 2012](#); [Piketty 2014](#); [Zucman 2014](#); [Alvaredo et al. 2017](#)) but the basic conclusions are clear. In the United States inequality declined during the 1930s and 1940s (the richest 1% of all households claimed 28% of all income in 1928 and just above 10% in 1950) and the post-1950 economic expansion reduced the share below 10% by the late 1970s.

But this was not to be the new normal: the trend was reversed and by 2008 the inequality was back to its late 1920s level, and then it was

surpassed to reach new disparity highs: by 2016 the richest 1% of households claimed 39% of all income and the bottom 90% took less than a quarter ([Stone et al. 2017](#)). Similar reversals have taken place in a number of other affluent countries, including Canada and the United Kingdom (WWID 2017). As a result, since 1980 income inequalities (commonly measured by the Gini coefficient) have increased in every affluent economy, as well as globally. When this trend is seen on the national basis its most notable outcome has been the emptying of the middle, with most of the national means falling below the threshold of the middle class ([Milanovic 2012](#)).

The world's fastest-growing economy has also experienced the fastest shift in inequality. Inequality in Maoist China, with its shared miseries, was low and it remained so during the first years of economic modernization: in 1985 the Gini coefficient was 0.24. Subsequently, China has seen a sharp reduction of poverty, but also a substantial increase of inequality. By 2010 China's Gini coefficient reached 0.53–0.55, considerably higher than the US value of 0.45 and ranking among the highest recorded inequalities worldwide, particularly in comparison with countries that have comparable or higher standards of living ([Xie and Zhou 2014](#)). For comparison, the Standardized World Income Inequality Database put China's Gini coefficient at 0.5 in 2013 ([Solt 2018](#)). China also faces considerable inequality of opportunities (gaps in access to certain financial services and unemployment insurance coverage), regional disparities, and continuing rural-urban gap.

Finally, another brief reminder that the categorization used in appraising past structural changes may be misleading in new circumstances. New forms of manufacturing are now often direct results of basic and applied research conducted at universities and laboratories whose funding comes from governments (US national laboratories being the prime example of this funding), industries, and foundations. How should we then classify the researchers? Are they a component of the manufacturing sector or of education or of government services? Desktop-based three-D printing of prototypes means that many industrial designers are now also de facto manufacturers, and some, producing unique designs (such as prostheses or art replicas), will become actual sellers of objects.

And upgrading of programs running complex sequences of robotized operations in industrial assembling means that this form of manufacturing

could not exist without the requisite software development. Moreover, these reminders about dissolved boundaries between economic categories could be just as easily extended to all primary activities, be it high-yielding crop cultivation (enabled by hybrid or genetically modified seeds and aided by remote sensing, satellite-based mapping, and GPS-guided application of fertilizers) or the exploration and extraction of hydrocarbons (aided by complex computer models and by continuous electronic logging while drilling, a feat impossible without high data-processing capabilities).

Indeed, it is easy to conclude that without these service sectors components it would be impossible to maintain record crop yields or record shares of recovered oil and natural gas. These realities are perfect examples of what might be seen as the end of structural transitions: modern economic production fusing the activities that could have been previously categorized in three classic sectors but that now form new inseparable synergistic wholes. And while some of today's claims regarding the imminent remit of artificial intelligence may be exaggerated, there is no doubt that increasingly common adoptions of higher-level software will push many economic activities into this new category of fused structures.

Material Abundance, Mobility, Information, and Communication

Abundance of material possessions, frequent travel and massive information flows are among the most notable accomplishments of modern civilization, all in stark contrasts with premodern societies. Before the transitions all but a tiny fraction of populations lived with a limited amount of simple material possessions; had their travels confined to nearby villages, pastures, or market towns; received sporadic information about the world beyond their immediate ken; and relied on verbal communication to transact everyday chores and to pass on their (sometimes remarkably rich) oral histories. Of course, there were many important nuances and notable departures from dominant realities and prevailing means.

Some premodern societies, even some foragers, enjoyed relative material abundance, compared to the lives of their not-too-distant contemporaries. The contrast between the settled fishers on the Pacific coast of North America—with their substantial cedar houses, remarkable wooden carvings

(masks, totem poles, canoes), and cedar bark and cattail weavings—and the tribes surviving in the boreal forests or in the northernmost reaches of America's Great Plains with the barest minimum of material possessions is an excellent example of such differences. Ancient mercantile societies had to maintain extensive networks of information in order to carry on with their trade and to engage in prospective exploration of new opportunities: Phoenicians, with their far-flung settlements around the Mediterranean and with their bold voyages (venturing into the Atlantic) were the early pioneers of this information-rich conduct ([Quinn and Vella 2018](#)).

And the contrasts widened during the early modern era when richer strata of urban residents reached the stage that might be described as an incipient consumer society seen in the paintings of the interiors of houses in Delft or Amsterdam during the country's Golden Age of the 17th century ([Franits 2004](#); [Shawe-Taylor and Buvelot 2015](#)). Their information and communication horizons were also much wider in comparison to their ancestors just a few generations ago, as ships of the East India Society brought not only goods but also news and descriptions of societies in distant continents, and as expanding book publishing was supplying new demand for volumes ranging from histories to cookbooks.

But this incipient material affluence and wider access to information were restricted to urban elites (including the new risk-taking intercontinental traders), while the lives of peasants remained materially deprived and illiteracy prevented their access to the rising flow of information. I have already covered two key components of the transition to abundance—increased food supply and high per capita flows of primary energy—and here I will turn first to different indicators of modern mass consumption. I will do that by tracing the overall increase in flows of materials and water (a neglected component of rising consumption) and then by surveying the preconditions, stages, and consequences of the shift from subsistence to adequacy and then to ostentatious waste of resources. I will close the chapter by looking at revealing indicators of mobility and by recounting the exponential ascent of communication capabilities and even more impressive growth of ways to generate, capture, and store information.

Consumer societies

Transitions to consumer societies could be traced in many ways. An economist might follow the share of national product derived from nonessential (excluding food, energy, and shelter) consumer spending. A historian of technical advances might trace the ownership of cars, household appliances, or electronic goods. A sociologist might suggest following the shares of meals eaten away from home or monies spent on branded luxury products. Perhaps the best way to appreciate the distance traveled in terms of overall physical consumption during the transition from traditional societies to modern economies is to compare their per capita mobilization (throughput) of resources.

[Kestemont and Kerkhove \(2010\)](#) found that in an Indian village (Sarowar in Gujarat) in 1982 the flow of abiotic materials was negligible, while the annual consumption of biotic raw materials (food crops, feed crops, fuel, and construction materials, all expressed as dry matter) was more than 4 t/capita. In 1830 a small Austrian village (Theyern in Lower Austria) consumed annually about 5.5 t/capita, virtually all of it as organic materials ([Haas and Krausmann 2015](#)). Similarly, my calculations for small European (German and French) early-19th-century villages with mostly brick or stone houses show the average annual flows of 1–2 t/capita of abiotic materials (mostly for construction, with small amounts of metals for farm implements, carts, horseshoes, and tools and pots) and 4–5 t/capita of dry organic matter for totals of 5–7 t/capita.

Comparison with material flows in modern societies is critically affected by the choice of analytical boundaries ([Smil 2014](#)). The account can be limited just to direct material inputs: that is, to all organic materials, fossil fuels, and minerals (water and air are usually excluded). Given the extent of international exchanges, it should include all imports. A broader delimitation includes all hidden material flows that are translocated during the process of extraction but are not used in the production of goods and services. These flows are dominated by material moved by quarrying, mining, constructing, and dredging, with lesser contributions from discarded crop and forest residues, and, as expected, are much more difficult to quantify than are the direct inputs.

If we take the broadest definition and include all hidden flows (but exclude water and air), annual material flows during the last decade of the 20th century averaged around 85 t/capita in the United States, Germany, and the Netherlands and nearly 50 t/capita in Japan ([Adriaanse et al. 1997](#)).

Hidden flows accounted for 55–75% of these aggregates and abiotic flows (construction materials, fossil fuels, metals) are dominant. The contrast between total annual material requirements of 5–7 t/capita in traditional rural societies and 50–85 t/capita in modern economies amounts to an order of magnitude, dominated by minerals whose extraction entails enormous indirect mass flows.

Restricting the account to just direct material inputs and tracing them over a long period of time confirms the magnitude of the mass-flow gain. US data allow us to trace the increase of basic non-fuel and non-food resources during the 20th century ([Matos and Wagner 1998](#); [Matos 2017](#)). Annual per capita flows of these materials rose from 1.9 t in 1900 to 12.1 t in the year 2000, more than a sixfold rise in a century. But by 1900 the United States was already a fairly advanced industrialized economy and hence it is clear that when the comparison began with the average flows typical of the early 19th century (for overwhelmingly rural America) we would see more than a tenfold gain. As expected, the importance of organic materials (wood, fibers, leather) declined from about 46% of the total mass in 1900 to just 5% in the year 2000, while the share of bulk construction materials (crushed stone, sand, gravel) rose from 38% to about 75%.

Yet another revealing way to illustrate the transition is to look at China's post-1980 record ([Smil 2014](#); [NBSC 2019](#)). Between 1980 and 2019 the production of cement had increased nearly 28 times (accounting for 54% of the global production), and in recent years China has been emplacing every three years more concrete than the United States did during the entire 20th century. During the same four decades China's plate-glass production rose 38 times (to nearly 70% of the global total) and output of raw steel rose more than 27 times (to 53% of the global total). China's increase of material requirements has no precedent in its speed but Japan's gains following the Meiji restoration have been of a similar order of magnitude ([Krausmann et al. 2011](#)). Total mass of consumed materials rose 40-fold between 1878 and 2005 (but mostly since 1950), and this increase translates to a 15-fold per capita gain.

All of these comparisons of order-of-magnitude increases exclude water—and yet water is the resource whose absence limits our immediate survival even more than a temporary lack of food, and whose adequate supply (aside from the dominant use in crop production) is required to maintain public and private hygiene and is indispensable in industries

ranging from ferrous metallurgy to food processing. Minimal use in preindustrial rural settings in arid regions or in places where water for household use has to be carried for more than 500 m was less than 10 L/day and typically no more than 20 L/day, a simple mean from a meta-study including more than 50 actual measurements from Asian, African, and Latin American countries is 29 L/day with the extremes of 2–113 L/day (Tamason et al. 2016)

In contrast, domestic per capita use of piped water in urban areas of affluent countries (including water for drinking, cooking, clothes washing, dishwashing, bathing, and toilet flushing) ranges from less than 100 L/day in some European cities to more than 300 L/day in some North American metropolitan areas (IWA 2016). In order to get a representative multiple, I will assume 30 L/day (almost exactly 11 m³/year) in traditional rural settings and, conservatively, 120 L/day (nearly 44 m³/year) in modern cities. The former mean is a reasonable assumption, as 20–40 L/day are seen as necessary minima for drinking, cooking, and sanitation, when we keep in mind that in many traditional settings no water is used for waste disposal because defecation in the open or pit latrines were (and still are) common. The resulting fourfold average increase of water demand is only a smaller part of the overall difference created by the transition to modernity.

Comparing the annual freshwater withdrawals of premodern countries with those industrialized societies that do not withdraw water for irrigation (because those that do have their water demand dominated by this sector) shows much larger differences than do comparisons limited to household use. The former rates were on the order of 15–20 m³/capita, while the rates for affluent non-irrigating economies with adequate precipitation and relatively good water resources range from about 200 m³/capita for the United Kingdom to about 500 m³ for France, with higher rates for the Netherlands and Japan. Transition from premodern rural economies to modern industrialized societies has been thus associated with yet another order of magnitude increase, that of withdrawals of fresh water.

Comparisons of dwellings areas capture only a part of the overall gains in the quality of housing. Small village houses provided just 50 m² of living space (which was, commonly less than 10 or 8 m²/capita)—but poor city apartments were often even smaller: for example, as recently as 1972 the minimum size specified for two-room apartments in France was just 46 m²

and about 30% more than the 35 m² required since 1922. And even in the United States, the average house in 1900 was no larger than 90 m². Even in affluent countries the major gains in living space had to wait until after World War II, with recent averages ranging from about 250 m² for new US family houses to 100 m² for Japanese apartments.

But tracing just the areal growth ignores many qualitative gains that make today's housing far superior to anything widely available not only before 1900 but even to standard living spaces before 1950. piped-in water, indoor toilets and bathrooms, some kind of central heating, and major appliances are now standard—while the 1954 census showed that fewer than 60% of French households had running water, just 25% had an indoor toilet, and a mere 10% enjoyed a bathroom and central heating ([Prost 1991](#)). Good sanitation came decades after electricity and gas heating became common and generations after living spaces began to fill with new acquisitions: in sanitary/hygienic regards the transition to modernity was notably delayed.

The acquisition of an increasing range of higher-quality (initially seen as luxury) products is one of the more fascinating aspects of the economic transition. Werner Sombart believed that the pursuit of luxury was the leading driver in the development of capitalism. He ended his book by writing ([Sombart 1913](#), 206): “So zeugte der Luxus, der selbst, wie wir sahen, ein legitimes Kind der illegitimen Liebe war, den Kapitalismus.” (Thus, luxury, which, as we have seen, was itself a legitimate child of illegitimate love, begot capitalism.) This notion has a great deal of support. Gradual de-moralization of luxury ([Berry 1994](#))—that is, loss of its traditional association with corruption and vice— opened the way for increased output and trade in nonessential products and many thinkers endorsed the link between the pursuit of luxury and growth of commerce and industry during the 18th century ([Franchetti 2013](#)).

[Pomeranz \(2000\)](#) assigns the arguments about the rise of luxury to two main groups. The first one, following Sombart, proceeds from the objectification of luxury by wealthy people boasting of enviable possessions rather than of large retinues to eventual imitation of these acquisitions by growing segments of urban population that could afford high-status consumption. The second argument assigns the leading role to smaller, less expensive products (clothing, small jewelry pieces) and, above all, to fancy foods (sugar, coffee, tea, cocoa) that were exotic luxuries at the

beginning of the 18th century but became commonly available two centuries later.

But concentrating on luxuries obscures the more fundamental rise of consumer societies based on the acquisition of better goods of everyday use. This consumption progresses in three basic steps. Basic possessions that were often absent or in short supply among low-income groups in premodern societies come first: a bed instead of straw strewn on the floor, another change of clothes. Different stages of small comfort came next: this vast category includes everything from basic furniture (chairs and sofas replace stools and benches) to kitchen equipment (cooking moves from a single blackened pot hanging in the fireplace to metal pots on a stove). Eventually, many former luxuries (from branded athletic shoes to designer handbags) become widely accessible, while the ceiling for the category of most ostentatious purchases keeps constantly rising: prices for the most expensive houses, yachts (actually massive motorized vessels), and paintings have now reached hundreds of millions of dollars.

No other country provides such rich materials for studying the earliest phases of this shift toward a consumer society than does France of the 18th century. Family budgets were first explored by Sébastien de Vauban (a famous military engineer and eventually a Marshal of France) in his *La dîme royale* published in 1707 and further inquiries by Pottier de La Hestroye, Félix Le Pelletier, and Henri de Boulainvilliers followed soon afterwards, showing how little was left over after buying food for a typical family of four (Roche 2000). In the early 1720s food required about 80% of the family income; four decades later the share was still about 75% even among big-wage earners, with less than 15% spent on clothes.

Earnings increased in the 19th-century cities but the progress toward consumer society was slow. Perrot and Guerrand (1990) describe crowding, slums, peripheral shantytowns, and rapid urban decay that brought little improvement for masses of new migrants as observers wrote about workers living like animals. Conditions remained primitive in many villages: houses with thatched roofs and rickety outside staircases to access the upper floor that were as much workshops and storage rooms as dwellings. And, as already illustrated with the diffusion of French sanitation, the real shift took place only during the 1960s.

For the 20th century excellent US data explain the foundations of the transitions to a consumer society and chart their detailed trajectories (USBC

1975; USDL 2019). The key driving forces of higher consumption were a declining family size (the average falling from 4.9 to 2.5 people), the rising share of female employment (from <20% to nearly 50%) and soaring household spending with the mean rising from \$769 in 1901 to about \$40,000 in the year 2000. At the same time, the necessities of life became more affordable: in 1901 the average US family spent 85% of its disposable income on food, utilities, and housing; a century later that share was down to 50%. Expenditures on food declined from nearly 43% to 13% and those on clothing fell even a bit more, from 14% to just above 4%, while housing's share rose from 23% to 33%, reflecting substantial increase in the size of dwellings and their standard amenities.

Initial stages of mass consumption are often marked by high gross saving rates—peaks were about 25% in the United States during the 1960s, 40% in Japan of the late 1980s, exceptionally high at 50% in China in 2010 ([CEIC 2017](#))—and by purchases of major appliances (refrigerators, washing machines, electric stoves, radios, and TVs). Gradually, private consumption becomes the leading share of GDP growth and it now accounts for about 70% of GDP in affluent countries. As the basic needs are satisfied, mass consumption enters the stage of diversification with the market catering to an enormous range of preferences for goods and intangibles, with the choice of experiences ranging from inexpensive family trips to theme parks to pricey ship cruises to “exotic” destinations.

Consumers begin trading up, both in terms of higher quality (a preference for well-known brand names and for more expensive imports) and by choosing products that were either absent or bought only in small amounts when incomes were lower. These items range from traditional luxuries (jewelry, cosmetics, spirits) to new beverage and food choices that include now ubiquitous purchases of bottled water (mineral, spring, flavored) or imported fruits, and from convenience goods (precooked meals, diapers) to fashionable items that include mobile phones and sports shoes. Credit becomes more readily available and household debt as the share of GDP rises. By 2017 this share was just 11% in India, nearly 50% in China, almost 80% in the United States, 100% in Canada, and 128% in Switzerland ([Bank for International Settlements 2019](#)).

This is also an apposite place to bring in the results of inquiries into happiness or satisfaction with life, a new branch of behavioral studies that has become popular during the past decades. The latest (2015–2017) global

ranking of happiness confirms an ancient adage of not being able to buy it. Japanese homes are stuffed with products but much poorer Colombians (their income is a third of the Japanese average) feel happier, ranking 43rd compared to Japan's 58th place ([Helliwell et al. 2019](#)). And the contrast of Guatemala (27th in the global happiness ranking) to South Korea (54th) offers an even wider gap, as the Korean purchasing power is five times the Guatemalan mean!

Nevertheless, lures of new goods and new experiences remain potent even in affluent societies, and the notion of voluntary moderation after reaching a sufficient level is unrealistic precisely because the definition of satisfaction and sufficiency, fueled by aspirational advertising and by our species' natural propensity for social jockeying, has been a constantly rising target. In that sense the economic transition from subsistence to surfeit is still very much unfolding. After they got color TVs and air conditioning most Americans could not imagine lives without them; now these goods are taken for granted and Americans now say they could not live without mobile phones and social networks, products that were not even on the market just a few decades ago.

Mobility

Transition to mass-scale mobility has depended on the provision of public transport—scheduled commercial services provided by railways, shipping, buses, airlines—and on the private ownership of bicycles and motorized vehicles. As with other transitions, this has been a sequentially unfolding process both in terms of specific transportation modes and in terms of national progressions. The first substantial gains were brought by steam power deployed on railways and in shipping since the 1830s. The United Kingdom pioneered the process and its progress was quite rapid, with peak growth rates of new railway lines reached already during the 1840s (at more than 1,500 km/year) and with the total number of passengers rising from 200 million during the early 1860s to 600 million by 1880 and surpassing 1 billion by the end of the 19th century ([Bogart et al. 2018](#)).

Maximum distance covered on a trip commonly undertaken by a typical inhabitant of a traditional society would be mostly just a few kilometers (2–8, 10^0 km) visiting a nearby market town, rarely a few tens of kilometers (10^1 km) on a multi-day journey when one was traveling to the closest large

city or a capital. Horse-drawn transportation increased the typical daily reach to the maximum of about 100 km (just reaching 10^2 km) for fast mail coaches. Railways routinely lengthened the maxima to 10^2 km (London to Birmingham 162 km, Paris to Brussels 264 km) and before the end of the 19th century many well-off people traveled hundreds of kilometers for vacations in mountain or sea resorts or to spas, and tens of thousands of Russians embarked on repeated (even annual) trips of thousands of kilometers from Saint Petersburg to Paris (about 2,800 km) or from Moscow to the French Riviera, more than 3,000 km. The latter distance is almost exactly equal to that of America's first transcontinental rail link (3,007 km) completed in 1869.

Within decades of its origin during the 1830s, steam-powered shipping began to offer scheduled service among all continents, with the longest distances spanning 10^4 km: London to Sydney via Suez Canal (completed in November 1869) is 25,000 km, San Francisco to Hong Kong 11,200 km. With typical speed no higher than 30 km/h those two trips would have taken, respectively, more than a month and 15 days to complete. Inevitably, the days of mass-scale long-distance shipping were numbered once flying had become commercial. KLM offered the first scheduled flights in 1920 (358 km from London to Amsterdam) and by the 1930s in the United States and Europe there were many intercity links covering distances on the order of 10^2 km ([Grant 2017](#)).

Introduction of aluminum monocoque planes raised this maximum to 10^3 km: in 1935 the DC-3 had a maximum range of 2,400 km, and just before World War II the Boeing 314 Clipper (a hydroplane) was capable of nearly 5,900 km. Only 30 years later, in 1969, the Boeing 747 brought the maximum to nearly 10,000 (9,800 km) but only the plane's second variant (747-200) could fly more than 10,000 km (10^4 km). And we are now close to bridging the longest frequented route (Sydney to London, 16,983 km) by a nonstop flight: the longest scheduled commercial link is now Singapore to Newark at more than 15,000 km ([Rosen 2019](#)).

In 1800 the maximum commonly traveled distance by an average inhabitant of better-off countries was 10^0 to 10^1 km; a century later almost everybody could afford a trip of 10^2 km and tens of millions took journeys of 10^3 km by train or ship. Airlines began to move large numbers of passengers only after the introduction of jetliners (starting in 1958 in the

West) and on intercontinental flights only after the introduction of wide-bodied aircraft (starting in 1969). In 1970 the world's airlines carried 310.4 million passengers; by the year 2000 that total had more than quintupled to 1.67 billion and the volume had doubled between 2005 and 2019 to about 4.2 billion ([World Bank 2019](#)). Flights of 10^3 km are now taken by a few billion people every year and tens of millions fly one-way distances of 10^4 km. These statistics mean that in 1970 the world's average person took flight only once in 11 years and by 2018 once in 22 months, while an average American (babies included) flew every four months, an average German every eight months.

Because of the growing length of flights (Norwegian families to winter vacation in Thailand, Chinese tourists to Las Vegas or Venice) the growth in passenger-kilometers has been even steeper than the growth of passengers carried. As already noted (in [Chapter 4](#)), the global total rose from 28 billion pkm in 1950 to about 7.5 trillion pkm in 2017, the latter number being an equivalent of taking every person on the Earth for a 1,000-km flight ([Smil 2019a](#)). This record shows that the global transition to mass-scale flying still has a long way to go; on the other hand, its future course may be greatly affected by economic downturns, by kerosene prices or, above all, by a rapidly progressing global warming. The unmet demand, however, is still measured in billions of new passengers and trillions of additional pkm.

When measured in maximum distance covered by a traveler in a day, the transition to modernity has increased the mobility by up to four orders of magnitude since the 1830s. Another way to look at the rising mobility is by focusing on its two principal categories of work- and leisure-related travel. Most of the travel in the first category consists of daily commuting, but much longer journeys to undertake specific tasks or to attend meetings have become more common in globalized economy, and are often of a longer duration. Commuting in premodern societies was primarily limited by the distance that could be repeatedly covered by walking; once this stricture had been removed by the expansion of railways, commuting distances increased, thanks to faster trains and to affordable car ownership.

In the United States the latest American Community Survey shows about 154 million people commuting, with 85% driving (76% alone) and just 5% using public transportation and spending, on the average, about 25 minutes to get to work (ACS 2018). Frequent commuting means that the United

States retains the primacy in average distance driven by a vehicle per year: it rose from less than 8,500 km in 1921 (the first year of such data) to 16,500 km by 1970, and it reached a new record of 19,500 km in 2016, more than 60% higher than the EU mean of about 12,000 km (BTS 2019). But there are clear signs of saturation: both the vehicle ownership per household and the average distance driven per household peaked in 2006 at, respectively, 2.05 and about 39,000 km/year ([Sivak 2017](#)).

In contrast, in Japan about 85% of commuters use trains and they average about 80 minutes a day in traveling to and from work, with those working in Tokyo spending 102 minutes in total ([NHK Cultural Institute 2015](#)). A conservative global estimate is that commuting by some 2.5 billion people spending 50 minutes a day adds up annually to nearly 60 million years of life, an enormous waste of human potential and generally a detestable experience that is commonly accompanied by stress and discomfort (also by sexual harassment) and that results in crowding, traffic congestion, and excessive air pollution.

This may be the least desirable way of increased human mobility—but its rewards are job opportunities and earnings available only in cities—and it remains to be seen how many employees will be eventually able to work from their homes: future potential for telecommuting is undoubtedly large, but in the past the practice's downsides have been often ignored and its promise has been chronically exaggerated ([Glass and Noonan 2016](#)). And a great deal of leisure mobility has now acquired many negative attributes, an inevitable development, given the growing scale of these endeavors and their concentration on a relatively small number of now globally iconic destinations.

Mass tourism is a part of modern discretionary spending on experiences rather than on purchases of additional goods, a special category of consumerism that ranges from attending professional sports matches and contests to the so-called ecotourist expeditions, and it does so with a steadily widening orbit. Leisure travel has a long but largely elitist history and some of its description from the 18th and 19th centuries—including Tobias Smollett's *Travels through France and Italy* (1766) or Johann Wolfgang von Goethe's *Italienische Reise* (1816–1817)—remain among the classics of Western literature.

For a long time, this kind of travel also had strong cultural and historical components. This was particularly true about the Grand Tour, the early

modern custom among young rich English men and women (suitably chaperoned) to visit sites in France and Italy ([Chaney 1998](#)). After 1863, varieties of this experience were gradually commercialized by Thomas Cook, the founder of the eponymous travel company that made international travel more affordable. In Europe, leisure travel and trips became relatively common before World War I. Destinations ranged from seashore and spa towns to famous cities and places of religious pilgrimage (Lourdes, Santiago de Compostela, Częstochowa), and the travel was overwhelmingly during the summer months (winter mountain holidays are a more recent invention). But the two world wars, the intervening economic crisis, and post-1945 reconstruction delayed the takeoff of mass-scale tourism—driven by higher disposable incomes, by car ownership, and by more affordable flying—until the 1960s.

In 1960 there were just 69 million international tourist arrivals, that total had more than doubled by 1970 (to 166 million), and a steady expansion pushed it to 680 million by the year 2000 and to 1.4 billion in 2018. Europe receives half of the flow (710 million) and the East Asia–Pacific region a quarter ([WTO 2019](#)). France remains the top destination (receiving nearly 89 million visitors in 2018), with Spain, the United States, China, and Italy completing the top five. While most tourist traffic still means traveling to neighboring countries (92% of Hong Kong’s visitors are from East Asia; 78% of tourists in France come from Europe), intercontinental trips have become routine as airlines have introduced thousands of new direct flights between the second-tier cities, many at discount prices to maximize their load capacity.

China’s outbound tourism is the latest, and a quite unprecedented, surge of this activity and now the leading cause of “overtourism” plaguing many destinations. Chinese expenditures on international tourism surpassed the US total in 2012 and by 2017 they were nearly twice as high (\$257 vs. \$135 billion), with Germany the distant third at \$81 billion. Although Germany remains the world leader in relative terms, spending about five times as much per capita as China and more than twice than the United States, the country’s outbound tourism has shown no signs of growth since the year 2000, just considerable fluctuations (WTO 2018). Similarly, French, South Korean, and Australian travel appears to be saturated, while the American departures are still rising.

Post-1950 growth of international tourism fits perfectly a logistic curve that is still in its early stages of ascent and whose continuation points to some 4.3 billion travelers by 2050, a projection that would mean that, on the average, almost every second person (expected population of 9.7 billion) would take an international trip in that year. That level of mobility is painful to contemplate, as mass tourism has already had destructive impact on many destinations, leading to the imposition of visitor limits (the Galapagos Islands, the Inca Trail in Peru, Bwindi National Park in Uganda) and to numerous new calls for imposing restrictions (including Venice, Italy's Cinque Terre, Canada's Banff National Park in the Rockies) and to actual closures of some damaged Asian beaches. Other common examples of undesirable impacts range from large-scale conversions of natural mountain landscapes to create ski runs to mega-ship cruising, recently the fastest growing segment of the industry.

Transition from large-scale to mass-scale international tourism is thus yet another shift emblematic of globalized modernity whose net appraisals (service jobs vs. environmental deterioration) is already yielding many negative outcomes. And appraising the extraordinarily rapid and pervasive increase in available information and ubiquitous access to instant communication is yet another difficult exercise in judging the outcome. Once again, indisputable benefits of a computerized world and of unprecedented data flows must be weighed against the (voluntary and involuntary) loss of privacy, enabling of all kinds of criminal activities, decline of reading and contemplation, and weakening of direct personal interactions, to say nothing about spreading false information on a previously unimaginable scale and interfering in elections.

Information and communication

As explained earlier in this chapter, [Mokyr \(2017\)](#) sees this duo as the prime movers of modernization. New information was communicated by books, pamphlets, mail, and personal contact across Europe among the creators of knowledge-based society. Even those who do not fully share Mokyr's thesis must concede that richer flows of information and easier means of communication have had the fundamental role in the transition from agrarian to industrial societies—and even more so in the unfolding transition to ever more computerized electronic economies, the shift now

commonly subsumed under the label of the coming pervasive artificial intelligence. These assertions and expectations have been addressed by many recent writings, including [Barrat \(2013\)](#) and [Bostrom \(2014\)](#). My goal is to review the pace, the achievements, and the consequences of past transitions to society that is now overwhelmed by information and that suffers from excesses of instant planet-wide communication.

In a notable exception to a common pattern, the first fundamental departure from millennia of written records and copied books—the deployment of the metal movable-type printing press by Johannes Guttenberg—took place before the beginning of the early modern era in 1500. As already noted in the opening chapter, the impact of this invention, commercially deployed since 1454, was remarkably rapid. Printed materials (books, newspapers, periodicals, statistical compendia, financial records, blueprints) remained the dominant depositories of information even after the commercial introduction of photographic images (starting during the 1830s), sound recordings (first by Edison in 1878), movies (starting in the 1890s), and television (initially during the late 1920s, on mass scales since the 1950s).

This world began to shift during the 1960s with the large-scale adoption of commercial computing, with the launching of spy and weather satellites, and with advances in medical imaging. All of these trends have greatly intensified and have been augmented first by mass-scale adoption of personal computers, VCRs, CDs, and digital cameras and since the 1990s by the global addiction to the Internet and personal mobile devices (telephone being a wrong name for devices combining functions that were previously served by watches, alarm clock, cameras, calculators, maps, radios, TVs, and more). The combination of these sources and depositories has resulted in unprecedented increases of available information and we can quantify the overall gain measured in bytes, units of digital information.

My best estimate is that the total textual information in all hand-copied libraries and private collections (mostly in Europe and Asia) before the advent of movable printing was on the order of 100 GB. That aggregate began to multiply rapidly. The typescript of a 1,000-page book is about 1 MB; a complete text of Shakespeare's plays is about 5 MB; a modern well-illustrated book is 20–40 MB. Images devour storage, moving images even more so: a single high-resolution photograph is 2–4 MB, a digital mammogram is 50 MB, and a movie is 2–3 GB. [Lesk \(1997\)](#) estimated the

textual holdings of the Library of Congress at 20 TB, all of its holdings (including audio, photographs, maps, and movies) at 3 PB, and all information stored worldwide at 3 EB, data that would mean a seven-order magnitude increase in stored information between 1450 and the year 2000. But that was an underestimate because during the 1990s digital storage was growing rapidly and by 2016 the worldwide supply of storage was higher than 16 ZB (Seagate 2017), rising 11 orders of magnitude (160 billion times) above the total reached in 1450 and expected to rise by another order of magnitude by 2025.

Aggregate rise of information has been accompanied by new mass-scale means of its diffusion. Editions of printed matter still required relatively energy- and labor-intensive distribution to reach their readers. Numbers of people who could be reached by broadcast information was initially limited by the power of early transmitters and by the sparse ownership of receivers but these constraints were rapidly eliminated by the emergence of many broadcasters sending out powerful signals and by the affordability of radio, and later TV sets. Human interest in receiving information has guaranteed that all new devices facilitating its diffusion have been eagerly adopted, making the transition from printed to broadcast information one of the most rapid shifts in modern history.

Vacuum tubes enabled a rapid diffusion of radio, transistors replaced fragile glass, and integrated circuits opened the way to information flows on an unprecedented scale (Figure 5.4a-c). Daily commercial radio broadcasts began in the United States in 1921 in Pittsburgh. A decade later half of all US households had at least one receiver, and 90% ownership rate was reached in 25 years in 1946 (Felton 2008). Television's adoption was delayed by the economic crisis of the 1930s and by World War II: the first working prototypes were available already during the late 1920s, sales of black-and-white sets began before World War II and took off only in 1947, and 90% ownership rate was reached by 1963. Transistors were put first into small radios but soon they made mass color TV ownership possible. Sales of the first tiny-screen color TVs began in 1954 and accelerated a decade later; by 1985 90% of US households owned at least one set. Adoption by 90% of US households was thus faster for radio (25 years) than for color TV (31 years). As in so many similar instances, diffusion by late adopters was even faster, with near-saturation levels reached in less than two decades.

(a)

No. 803,684.

PATENTED NOV. 7, 1905.

J. A. FLEMING.

INSTRUMENT FOR CONVERTING ALTERNATING ELECTRIC CURRENTS
INTO CONTINUOUS CURRENTS.

APPLICATION FILED APR. 19, 1905.

Fig. 1.

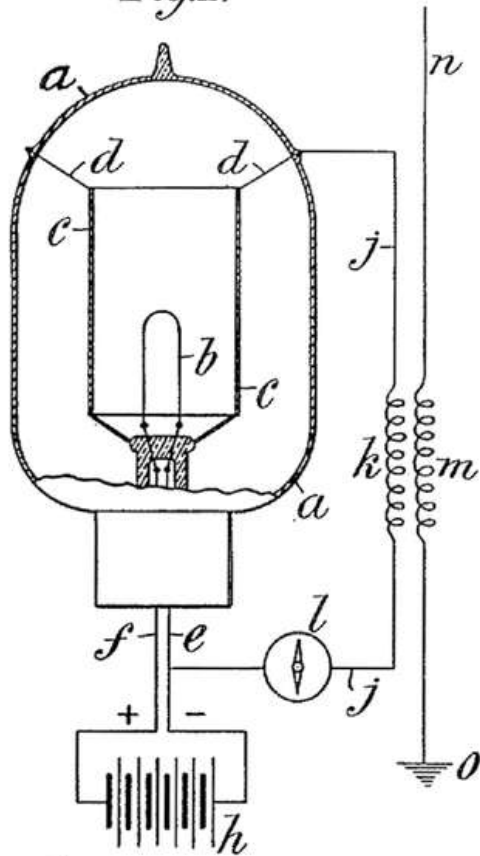


Fig. 2.

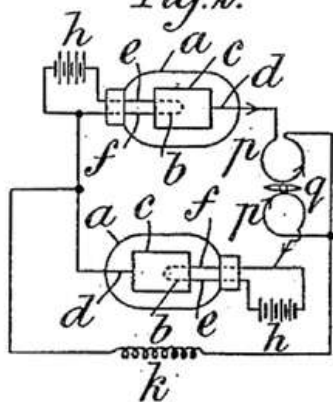
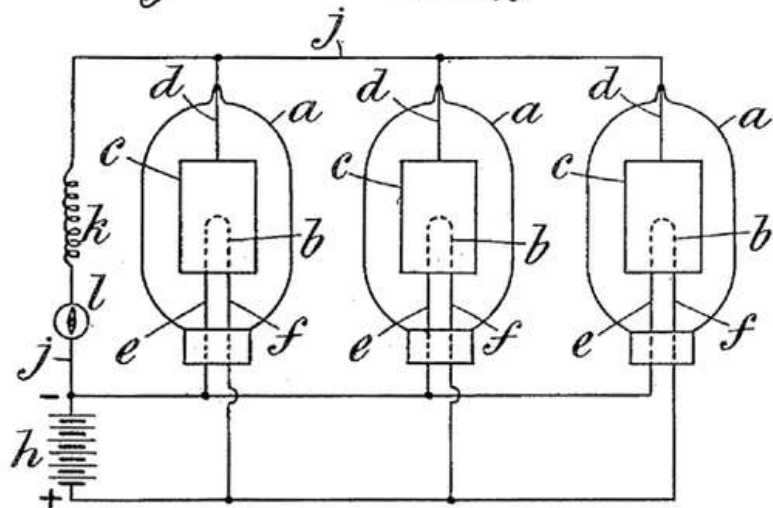


Fig. 3.



Witnesses

William H. Davis.
James J. Osborn

Inventor

John Ambrose Fleming
by his attorneys
Ratto Ratto Sheffield Ratto

Figure 5.4a-c The three key patents of the new information age: John Ambrose Fleming's 1905 diode patent; William Shockley's 1951 patent for "circuit element utilizing semiconductive material"; and Robert Noyce's 1961 patent for an integrated circuit. Images from the US Patent Office.

(b)

Sept. 25, 1951

W. SHOCKLEY

2,569,347

CIRCUIT ELEMENT UTILIZING SEMICONDUCTIVE MATERIAL

Filed June 26, 1948

3 Sheets-Sheet 1

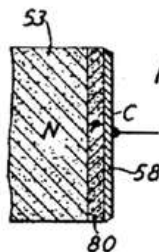
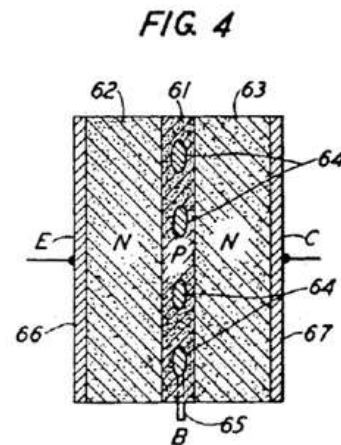
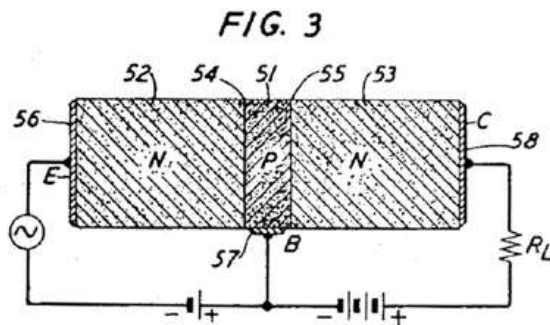
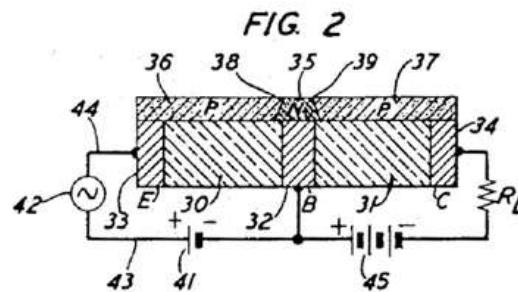
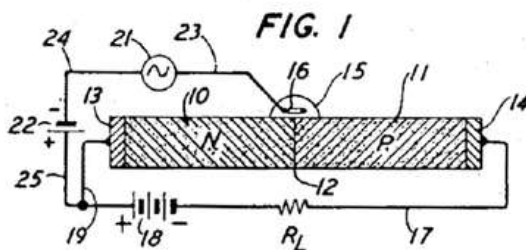
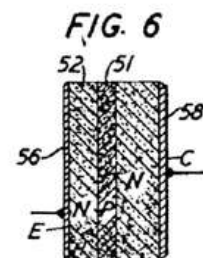
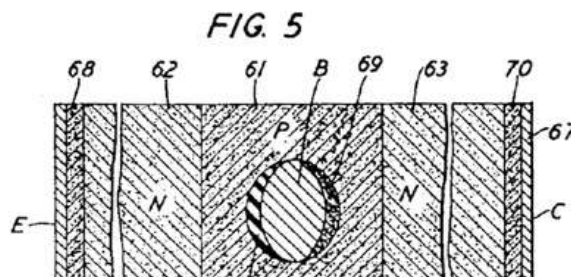
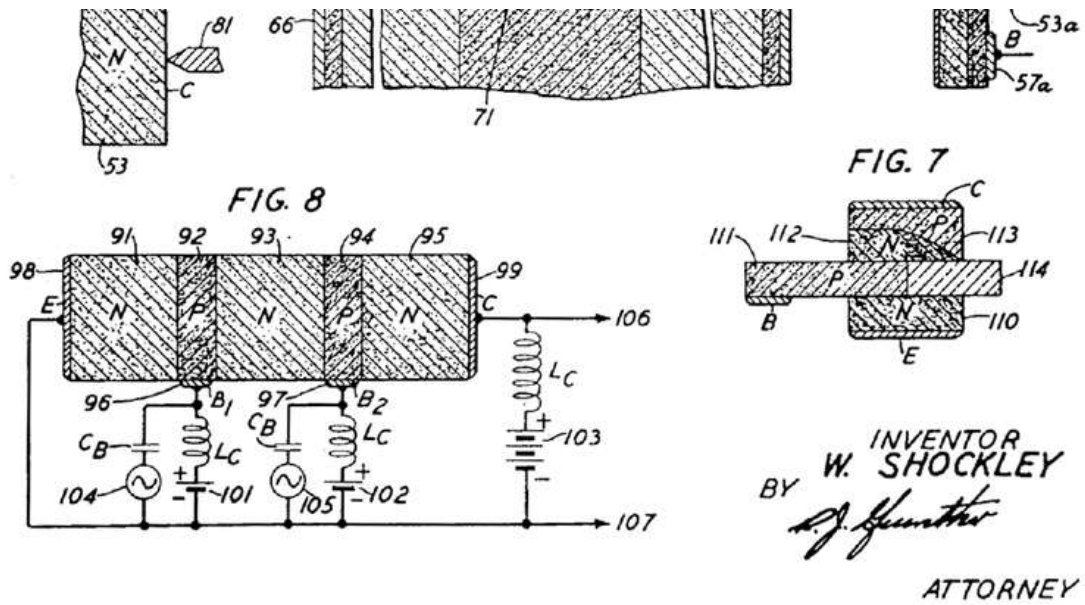


FIG. 3B





(c)

April 25, 1961

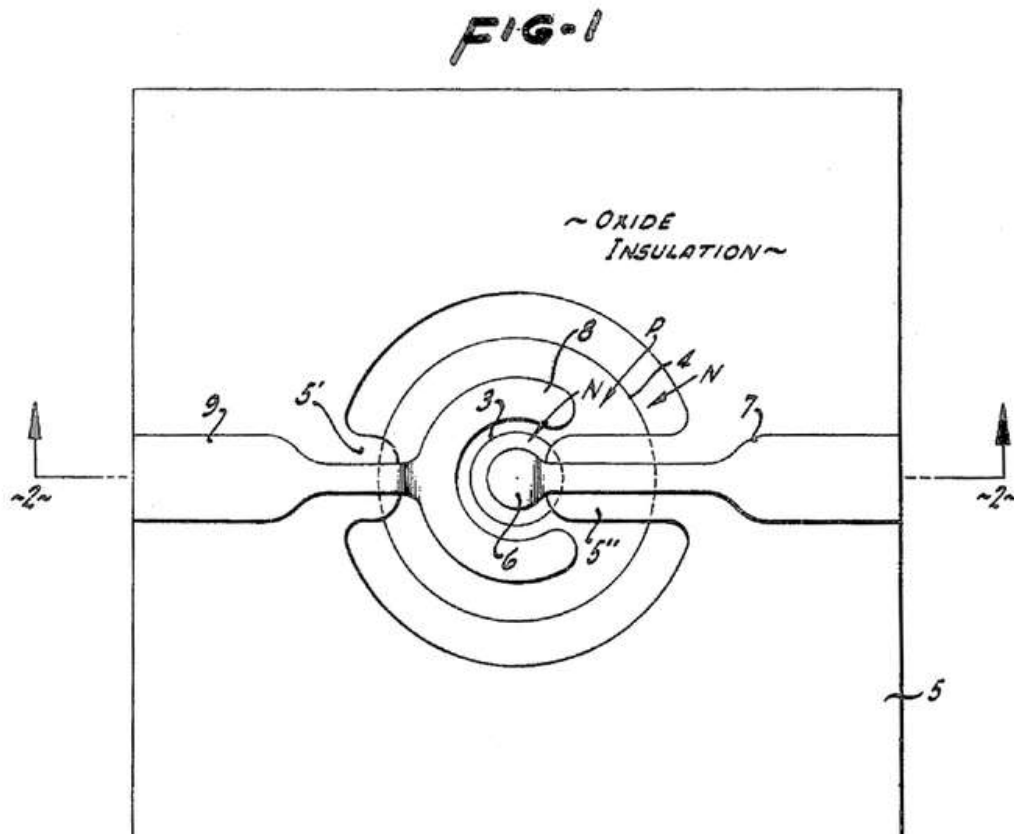
R. N. NOYCE

2,981,877

SEMICONDUCTOR DEVICE-AND-LEAD STRUCTURE

Filed July 30, 1959

3 Sheets-Sheet 1



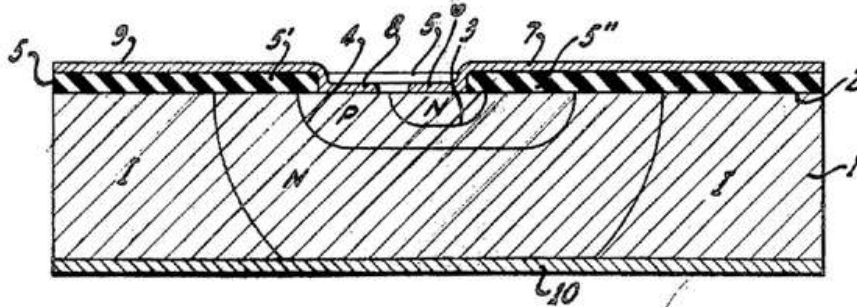


FIG. 2

INVENTOR.
 ROBERT N. NOYCE
 BY *Leppincott & Ralls*
 ATTORNEYS

Introduction of digital cable and HDTV with superior image resolution has not fundamentally changed the media's long-established role but it has contributed to a further increase of average watching time. That daily rate grew from five hours per household in 1955 to the peak of nine hours in 2009–2010, and nearly a third of the increase in average watching time since the beginning of broadcasting to its peak took place during the first decade of the 21st century before it finally began to decline ([Madrigal 2018](#)). Despite widespread availability of internet and mobile phones, TV watching continued to grow for another 15 years before finally declining—or not, as a part of it has shifted to watching the same broadcasts on smaller portable screens. In any case, in some countries that transition has been clearly completed to its mind-numbing saturation.

Broadcast information received an enormous boost with the widespread availability of wireless Internet. Access to the World Wide Web was originally available only in wired configurations. The growth of connections still depends on an expanding network of fiber-optic cables but

new satellite fleets are increasing the wireless access. The first widely used browser (Mosaic) became available in 1993 and just six years later half of adult Americans were using the Internet; this rate rose to 84% by 2015 and to 96% for 18–29-year-olds ([Pew Research Center 2015](#)). This transition is obviously complete in all affluent societies and the global growth is also becoming saturated. Worldwide Internet traffic soared from 100 GB/day in 1992 to 26.6 TB/s in 2016 ([CISCO 2017](#)) but my analysis of data collected by the Internet Domain Survey (ISC 2018) indicates that the number of hosts has conformed to a logistic curve that had its inflection point in 2008 and that might reach its asymptote around 2030.

The first technique of modern communication had become available long before the first new way of mass-scale information broadcasting: the telephone preceded radio by more than four decades, but even in the United States its adoption was slow during the last two decades of the 19th century. By 1915 30% of US households had a telephone but the diffusion rate slowed down during the 1920s (when radio ownership took off); it had actually declined during the years of economic crisis of the 1930s, reached 50% only in 1946, and rose above 90% only in 1970, nearly a century after the formation of Bell Telephone Company in July 1877. A new era began with the deregulation of telecommunications and with the introduction of affordable mobile telephony.

But contrary to a common belief, diffusion of new mobile devices based on high-performance solid-state electronics was not always faster than the adoption of vacuum-tube-based electronics: between 1925 and 1930 radio spread in the United States as fast as the mobile phones between 1995 and 2000 ([Smil 2019a](#)). Ownership of wireless phones experienced its fastest growth rates during the first 15 years of the new century. Worldwide sales rose by an order of magnitude (from 100 million to one billion a year) in just 12 years (between 1997 and 2009). In 2017 smartphone sales surpassed 1.5 billion units ([Gartner 2018](#)), and saturation may be reached at around 2 billion units.

The economic and social impacts of increasing capacities for instant and affordable connection and communication have been greatly potentiated by the rise of new, highly addictive forms of electronic interaction. The choices range from millions of blogs and YouTube postings to Facebook interactions: by 2020 the company had more than 3 billion accounts worldwide ([Facebook 2020](#)). As the capacities for data flow increased, text

had rapidly become a marginal component of these interactions, with the global traffic dominated by video and music streaming. Large and small conveniences and enormous information, organization, and learning benefits brought by these flows have been accompanied by many negative consequences.

As already noted, the loss of privacy; the theft of information, identities, and deposited monies; dissemination of misleading news and claims; and bold interference in political affairs of other countries are among the negatives that have received a great deal of public attention ([Carr 2011](#); [Nance 2016](#)). Much less is being said about criminal activities of every kind that have been enabled by the Internet and by mobile telephony and that are increasingly difficult to trace to their origins or about the prodigious environmental impacts of this new e-world. To begin with, electronic components and devices may be small but their energy and material intensities are exceptionally high.

A car weighing 10,000 times as much as a mobile phone (1.4 t for a sedan vs. 140 g for a smartphone) embodies considerably more energy but I have done aggregate global accounts that show an unexpected comparison ([Smil 2016b](#)). In 2015 global sales of mobile phones, laptops, and tablets added up to 550,00 t and their production required about one exajoule (1 EJ) of primary energy—while making 72 million cars (weighing 100 Mt) needed about 7 EJ. The first surprise: vehicles whose aggregate mass was more than 180 times larger than that of portable electronic devices needed only seven times more energy to make. But portable devices have short lives, and if we assume the average of two years the prorated energy inputs come to about 0.5 EJ/year of use. An average car lasts a decade, hence the second surprise: the prorated energy cost of global car making is 0.7 EJ/year, just 40% more than for portable electronics!

Consequently, such products should be built to last and to be readily recyclable (designed for convenient dismantling). However, the very opposite is true. Devices are deliberately made to fail early (the standard warranty span for consumer electronics is still only one year) and in the case of mobile phones the makers are exploiting the common quests for novelty and social standing by introducing new models at indefensibly short intervals—and yet they fail to provide widely accessible and reliable recycling options. As a result, the lifespan of an average smart phone has been only 17–22 months (Kantar Worldpanel 2017) and recycling rates

remain pitifully low. At least two other common consequences of the new e-dominated life should be noted: the reduction of direct personal interaction and the decline of book reading. The average American now reads only four books a year, and a quarter of Americans do not read any books ([Pew Research Center 2018](#)).

6

Environment

Unlike the grand population, food, energy, and economic transitions that have been all unfolding and interacting largely during the past two centuries, the beginnings of large-scale anthropogenic transformation of the Earth's environment predate this great concatenation not just by centuries but also by millennia. In order to put the more recent anthropogenic interventions into a historical perspective and to appreciate the scale of recent deterioration, as well as some notable positive changes, I must start the last topical chapter of this book with an extended explanation of the range and extent of premodern human assaults on the environment.

The oldest large-scale anthropogenic impacts resulted from the use of fire. We will never know its first deliberate use by hominins. [James \(1989\)](#) collected tenuous evidence for the use of fire in the Lower and Middle Pleistocene, as early as 1.7 million years ago. But the earliest convincing date for controlled fire is now nearly 800,000 years ago ([Goren-Inbar et al. 2004](#)), and the practice was common during the Middle Paleolithic (300,000 to 200,000 years ago), the period that ended with *Homo sapiens sapiens* displacing the European Neanderthals ([Bar-Yosef 2002](#); [Karkanas et al. 2007](#)). [Mellars \(2006\)](#) thought that controlled burning of vegetation could have been done in South Africa 55,000 years ago. In any case, over time the combination of accidentally (set by cooking fires) and deliberately set fires had to have a considerable aggregate impact, especially in drier environments.

The second and vastly more consequential large-scale human impact was the contribution to the extinction of megafauna. This process was a combination of human preference for killing large fatty mammals and of natural climate change. Archaeological evidence (tool marks on bones) shows that cooperative hunting of large herbivores (aurochs, deer, horses) was practiced already 400,000 to 200,000 years ago ([Stiner et al. 2009](#)). The practice was driven by the quest for high-quality protein and dietary

fat, a trait shared with our primate ancestors: both chimpanzees and bonobos are meat hunters ([Hohmann and Fruth 2008](#)). Wild meat of smaller species is essentially pure protein, while mammoths and other large species of megafauna (a species whose adult weight is in excess of 40–50 kg) had high shares of high energy-density fat, providing both the satisfactory feeling of satiety and the energy needed to survive in colder climates.

Late Pleistocene landscapes teemed with megaherbivores, including mammoths, woolly rhinoceros, giant deer, steppe bison, aurochs, and ground sloths—but all of these animals (and most megacarnivores that preyed on them) became extinct by the time human foragers began to form the first settled communities. Richard [Owen \(1861\)](#) was the first scientist to argue that hunting contributed to this extinction and Paul Martin's overkill hypothesis (a wave of mass-scale extermination of megafauna by migrating hunters) became a widely accepted explanation for the disappearance of North America's megafauna (Martin [1958](#), [1990](#), [2005](#)).

The latest research sees the late Pleistocene extinctions due primarily to climate and vegetation changes ([Pushkina and Raia 2007](#); [Allen et al. 2010](#)). Replacement of open grasslands by tree-dominated ecosystems created habitat fragmentation, and hunting could have contributed to a faster extinction of vulnerable species. Much like today's African elephants, the late Pleistocene megaherbivores created open grassy landscapes devoid of trees and also supportive of many smaller grazers ([Zimov et al. 1995](#)). Megafaunal extinction opened the way for coniferous taiga in higher latitudes, for deciduous forests in the more temperate zone, or for transitory communities of spruce and broadleaved trees ([Johnson 2009](#)).

We will never be able to apportion the shares of megafaunal extinction to natural and anthropogenic factors, but we are on firmer ground when we are appraising the third category of ancient human environmental impacts, land-use changes resulting in emissions of greenhouse gases. Land-use changes that began nearly 10,000 years ago with Neolithic cultivators converting grasslands, forest, and wetlands to croplands were initially limited by low population numbers and they were restricted to a few regions. Local loss of biodiversity and soil erosion were the most obvious environmental effects and it was assumed that even in the aggregate these transformations could not add up to any notable global impact.

Ruddiman ([2005](#), [2017](#)) challenged this conclusion by arguing that even the limited numbers of early cultivators began to make a discernible

difference some 8,000 years ago because of increased emissions of CO₂ from extensive land-use changes (primarily from deforestation and wetland reclamation), from releases of CH₄ from anoxic flooded soil (for rice cultivation), and from domesticated ruminants. This is an indisputable observation but its impact might not have been as large as claimed by Ruddiman, who concluded that by the start of the industrial era, human-induced emission of CO₂ and CH₄

had caused increases in the atmospheric concentrations of both gases equivalent to about half of the natural range of variation that had occurred previously. . . . These increases . . . produced a greenhouse warming effect that cancelled a large portion of natural cooling under way at high latitudes . . . our effect on global climate was now very nearly equal to that of nature ([Ruddiman 2005](#), 171).

The fourth large-scale premodern impact on the biosphere was the extensive deforestation in parts of Asia (North, Central, and Eastern China) and Europe (especially in the Mediterranean countries). This often enormously disfiguring transformation had three main causes: conversion of forests to croplands; demand for cooking and heating fuel; and requirements of producing color metals and iron. Copper smelting was a major source of Mediterranean forest destruction during antiquity, with 90 kg of wood needed to produce a kilogram of [copper \(Forbes 1972\)](#). Early iron smelting put great pressure on local wood resources, as it required as much as 20 kg of charcoal whose production needed up to 80 kg of wood, per kg of hot metal ([Johannsen 1953](#)). The adoption of better furnaces reduced these specific needs, but the overall scale of production kept on increasing.

In the early medieval period (around 900) forests covered about 70% of Central Europe (from Alsace to eastern Poland and from the Baltic and the North Sea to the Alps); by 1900 the share was down to 25% ([Schlüter 1952](#)), with most of this loss taking place before 1700. The most extensive forest clearing in the Atlantic and Central Europe was between 950 and 1350, the centuries called by [Bloch \(1931\)](#) *l'âge des grands défrichements*. [He et al. \(2008\)](#) put the Chinese forest losses between 1700 and 1900 at no less than 90 million ha, or nearly 40%, of the country's remaining forest cover in 1700. All of these anthropogenic impacts have intensified during the modern era and we must distinguish (as already explained in the introductory chapter) between two kinds of global anthropogenic changes.

The first category, exemplified by the emissions of greenhouse gases, refers to changes that affect the entire planet. Anthropogenic emissions of CO₂ (over 37 Gt in 2019) far surpass any other gaseous anthropogenic additions to the atmosphere but there are other fluxes whose magnitudes have risen to rival natural global flows. Most notably, emissions of sulfur oxides from fossil fuel combustion and metal smelting have been surpassing the combined global output by bacteria and volcanoes, and emissions of nitrogen oxides are most likely equal to all natural flows of NO and NO₂. Both of these fluxes are excellent examples of the other category of global problems, of the changes that are ubiquitous (found on all inhabited continent) but whose effects are confined to local, regional, or semi-continental impacts well known as acid deposition (or, less accurately, acid rain) and photochemical smog. Other items in this category belong to a large class of environmental degradations that range from soil erosion to dead zones in coastal waters.

This is an apposite place to note that some critics would dismiss these prefatory remarks concerning environmental changes as being fundamentally insufficient because we now live in the Anthropocene, a new geological era supposedly characterized by the dominant role of humans:

The Anthropocene concerns human impacts on the Earth System, not on the environment, and one cannot understand the emergence of the concept of the Anthropocene without an understanding of the radically new conception of the Earth System that emerged with Earth System science in the 1980s and 1990s. . . . The Earth System is not “the landscape,” it is not “ecosystems,” and it is not “the environment” ([Hamilton 2015](#), 103).

The first suggestion of a new geological epoch for the humans was made in the year 2000 ([Crutzen and Stoermer 2000](#)); work on the formalization of a new geological time unit began in 2009. In 2016 a majority opinion within a working group was that the Anthropocene was stratigraphically real and the recommendation was to formalize the distinction by using a mid-20th-century boundary with anthropogenic radionuclides associated with nuclear arms testing as the most promising marker ([Zalasiewicz et al. 2017](#)). I have considered this effort in the same way I see Hamilton’s quotation, namely that both of these arguments are as obvious as they are inaccurate. While the parts of the Earth system (lithosphere, hydrosphere, atmosphere, biosphere) are all linked by tectonic and biogeochemical

cycles, modern civilization has had profound impacts on only some of these interrelated components.

We may be important enough to warrant a new epochal label, mostly because of our unfolding effect on climate, not because of minute levels of deposited radionuclides. At the same time, the fundamental variables that make life on this planet possible—location in a rather quiet region of our galaxy, enormity of fusion-powered solar radiation, the Earth's shape, tilt, rotation, and eccentric orbital path around the Sun (the pacemakers of seasons and Ice Ages)—are all completely beyond human control, as are the megaforces of the planet's plate tectonics that rearrange oceans and continents and that generate earthquakes and tsunamis. Moreover, on an evolutionary scale we also face catastrophic threats due to large asteroid collisions with the Earth or extensive volcanic or magmatic eruptions. Our actions have, all too obviously, affected, transformed, destroyed, and defaunated the environment—but the ultimate controls of the planet's place and fate in the solar system are beyond our reach.

Regardless of any formal or informal designations, some anthropogenic impacts are inherently limited by the extent of ecosystems and by the planet's size (there is a finite area of primary tropical rain forest that can be cut down), and many processes can be traced by following obvious markers. Deforestation's trajectory is much like the demographic transition measured by the changes of natural population increase: from low to high to low. Precolonial New England inhabited by settled foraging societies that combined hunting and gardening had minimal deforestation rates. In 1700 forests still covered some 85% of Massachusetts; by 1870 their area was down to 30% of the state—but by 2015, with forests covering 61%, Massachusetts was the eighth most forested state in the union ([Foster and Aber 2004](#); [USDA 2015](#)).

And if saturated per capita availability of food signals the end of nutritional transition (at least in food energy terms), counterparts could be found in saturated and even impressively declining per capita rates of generating assorted solid, liquid, and gaseous wastes—or at least in increasing rates of their control. The latter instances range from proper water treatment to desulfurization of gases emitted from coal-fired power plants. On the other hand, there are many land-use changes and many degradative shifts whose rates remain unacceptably high. That large category contains, most prominently, tropical deforestation, reclamation of

coastal wetlands (including tropical mangroves), runoff of nitrogen-laden waters into the ocean, accumulation of solid wastes (including the latest rapid growth of electronic waste and plastic pollution in the ocean), and (in virtually all ecosystems) the loss of biodiversity. I use the division of impacts into land-use transitions, ecosystemic degradations, and global changes as a convenient (and not overly simplistic) classification in order to provide a systematic coverage of a multitude of overlapping and interacting changes that differ so much in their properties, spatial extent, and socioeconomic impact.

Land Cover and Land Use

One of the most stunning contrasts resulting from the grand transitions is a comparison of the global land cover in 1800 and in the year 2000. Because the first Earth-observation satellite, LANDSAT, was launched only in 1972, reconstructions of land cover/land use in 1800 can be only approximate—and comparison of the four global land-cover mapping projects shows many remaining uncertainties, with the highest errors arising from attributions to specific land-use classes whose definitions have many inconsistencies ([Congalton et al. 2014](#)). In any case, substantial losses of natural ecosystems and ongoing expansion of anthropogenic land uses are undeniable ([Ellis et al. 2013](#)).

Grazing land (pastures) and cropland have become the most extensive altered ecosystems, followed by settlements, industries (from extractive endeavors to factories and storages), and transportation facilities and corridors. Many of them often have displaced the most productive (alluvial) land or protective wetlands, or were built on land reclaimed from the ocean. These changes have been particularly transformative in the tropics (and most stunningly in the southern half of the Amazon Basin and in parts of monsoonal Asia) and on the North American and Eurasian plains. At the same time, the 1800–2000 contrast would show restoration of tree cover that was destroyed by premodern societies (natural regrowth as well as mass-scale planting of trees in parts of Europe, North America, and, most recently, China). Growth of the cities could be seen both as radiative expansions of old centers and as gradual fusion of adjacent settlements and formation of megacities, often along the coasts.

By far the best way to map changing urban, industrial, and transportation land uses is to look at nighttime observations, and yet even in this case the published totals differ by a factor of two. Columbia University's *Gridded Population of the World and the Global Rural-Urban Mapping Project* assigned 350 million ha (about 2.6% of ice-free land of 13.4 billion ha) to urban areas (GRUMP 2019) but [Cox \(2010\)](#) explained why that is a substantial exaggeration and why the actual 2010 total is about 110 million ha, or less than 1% of the world's non-glaciated land.

Nighttime satellite imagery has been also used to assemble the world's first inventory of impervious surfaces: land that is sealed by pavements (concrete or asphalt, also stone and bricks) to build roads, airports, ports, sidewalks, driveways, parking lots, and storage areas or that is covered by roofs. This inventory ended up with about 58 million ha in the year 2000, or 0.43% of ice-free land ([Elvidge et al. 2007](#)). As expected, China had the largest national total (about 8.7 million ha) but the United States, not India, ranked second with some 8.4 million ha. The highest national per capita rates (leaving ministates aside) are in high latitudes (Canada 350 m², Finland 320 m², the United States 300 m², Norway 235 m²); elsewhere the impervious surfaces amount to just 50–150 m²/capita.

The future of cities (and the extent of impervious areas) is linked more closely to population than to economic growth. Germany offers perhaps the most notable example. As a whole, the country's post-2008 economy has been doing quite well but population stagnation and decline in what was formerly East Germany means that recently only some suburbs of Berlin have been gaining while even such major cities as Leipzig and Dresden now have populations, respectively, about 20% and 12% smaller than their pre-WWII peaks. Such shifts presage the country's population future: Germany's population will drop from nearly 83 million in 2019 to about 68 million (a continued natural growth trend with lower immigration) or 73 million (a continued trend with higher immigration) in 2060 (FSO 2015). And in now depopulating Japan the capital is the only city that keeps growing: the second largest city, Osaka, now has about 15% fewer people than it had in 1960 and the population of Kitakyushu, the largest industrial city in the southern Japan, peaked in 1980.

Other regions where cities have already reached their greatest extents include most of Russia, Eastern and Central Europe, and large parts of Central Canada and the United States. In contrast (as already noted in

[Chapter 2](#)), the recent decades have seen more or less orderly but extraordinarily rapid growth of Chinese cities, and only slightly less rapid but uncontrolled and chaotic growth of cities in the rest of modernizing Asia and in Africa, where urbanization still has generations to run, as does the continuing destruction of tropical forests.

Deforestation and reforestation

Deforestation has been driven by a variety of demands: timber for housing (and until the late 1800s also for shipping), for uses in underground coal and ore mining (pit props), and in transportation (railroad sleepers beginning in 1830s), fuelwood for heating and cooking, and wood to make charcoal for households and industries, particularly for smelting of metals and production of bricks, tiles, and glass (Williams 2006; [Smil 2013a](#)). But the most important driver of deforestation has been the extension cropland and pastures, and this process been closely correlated with the rise of global population and with the improvement of typical diets.

There is little dispute about what constitutes cropland (land for growing annual or permanent food, feed, fiber, or energy crops) but FAO's Forest Resources Assessment listed some 650 definitions of forest ([FAO 2001](#)). All of them must impose the minimum area and minimum tree density (usually expressed as the share of ground covered by tree canopies)—and the recently used FAO criteria include any area larger than half a hectare (5,000 m², or a square with a side of not quite 71 m, a major reduction from the previous requirement of 100 ha) with trees taller than 5 m and with their canopies covering at least 10% of the ground (such a sparse coverage amounts, at best, to a woodland, not to a forest).

Moreover, the count can include younger and smaller growth as long as it is eventually expected to reach these limits and even areas that are temporarily barren but where the trees are expected to regrow, and such non-vegetated areas as forest roads, firebreaks, and small openings are included in the total count. At the other end of the forest definition spectrum would be a mature growth of tall trees whose canopies cover 90–100% of the ground, as in old-growth Pacific Northwest or Amazonian forests. And given the inevitable uncertainties involved in reconstructing the areas of preagricultural forests, all historical estimates of deforestation can be only approximate.

[Matthews \(1983\)](#) put the total pre-1980 deforestation at less than 1 billion ha (a reduction of about 15%). [Williams \(2003\)](#) made a similar estimate of 740–810 million ha of total pre-1978 forest clearings but [Richards \(1990\)](#) offered a substantially higher estimate of 1.39 billion ha cut down just between 1700 and 1995. [Ramankutty and Foley's \(1999\)](#) reconstruction of potential forest and woodland vegetation came up with 5.52 billion ha and they estimated that less than 5% of it was cleared by 1700 (down to 5.27 billion ha) and about 20% by 1992 (down to 4.39 billion ha). These numbers would indicate about 25% reduction of the maximum postglacial forest cover by the 1990s.

Because of different forest definitions, the assessments of total forested area published during the past three decades range between the lows of 2.9–3.4 billion ha (for growth with closed or partially closed canopies) by [Matthews et al. \(2000\)](#) and the high of 4.16 billion ha (and additional 280 million ha of interrupted woods) by [Saugier et al. \(2001\)](#). The latest assessment by the Food and Agricultural Organization (FAO) of global forest resources put the total 2015 area a fraction below 4 billion ha (3.999 billion ha), a loss of 1.4% in the first 15 years of the new century ([FAO 2015](#)). But the area of primary forests (containing only native species without obvious signs of human activities) was only about 1.28 billion ha, and just seven countries (Russia, Canada, Brazil, DR of Congo, the United States, Peru, and Indonesia) accounted for 75% of that total.

At their postglacial peak primary forests and woodland covered about 40% of all ice-free land, by 1800 their area was reduced by no more than 10%, and by the beginning of the 21st century it decreased by about 28%. Forests (as defined by FAO) now cover almost 30% of all ice-free land, while primary forest growth is now found on only about 10% of ice-free land. But, as always, the global totals and rates hide considerable national and regional differences.

Deforestation began to decline throughout Europe and North America as coal displaced fuelwood and charcoal and as steel and concrete became leading construction materials, while higher crop yields led to gradual abandonment of cultivation on poor soils and their revegetation. The resulting expansions of forested land were impressive: during the second half of the 20th century these gains ranged from more than 20% in Italy to about 33% in France ([Gold 2003](#)), and Europe's forests increased by 12

million ha between 1900 and 2005, an area roughly equal to all German forest and woodland (MCPE 2007).

And this trend has continued in the new century: the latest FAO forest assessment ([FAO 2015](#)) shows that in 25 years between 1990 and 2015 all large EU countries, as well as the most forested ones, have either increased their forest area (France by 0.7%/year, Italy by 0.8%/ year, Spain by 1.2%/year, Finland by 0.1%/year) or maintained the same tree cover (Germany, Sweden). The two nations with the largest areas of boreal forest, Russia and Canada, have seen their total areas almost unchanged. Deforestation has thus ended in many affluent countries, although in some of them the return of forest is not due to a complete cessation of cutting but to faster rates of reforestation. More forests have also become protected: in 2015 such areas (with various degrees of restrictions) were about 650 million ha of forests, or more than 16% of all forested area ([FAO 2015](#)).

Deforestation continues in many Asian, African, and Latin American countries but its rate has been slowing down. FAO's estimates of global deforestation rose from 12 million ha/year between 1950 and 1980 to 15 million ha/year during the 1980s and to about 16 million ha/year during the 1990s and then declined to around 13 million ha/year between 2000 and 2010 ([FAO 2015](#)). Moreover, because of rising rates of reforestation the deforestation rate was halved between the 1990s and 2010–2015, from 11.5 to 5.8 million ha/year. Deforestation rates remain unacceptably high in too many Asian, African, and Latin American countries. Given the biodiversity of tropical rain forests and their role in global carbon and water cycles, destruction of those forests remains a great concern ([Moutinho 2012](#); [Lawrence and Vandecar 2015](#)).

In Amazonia—the world's largest tropical forest biome, shared by Brazil, Venezuela, Colombia, Ecuador, Peru, and Bolivia—pre-1970 deforestation was minimal (a total of just 35 million ha) and the forest covered about 4.1 billion ha with the nearly 850 million additional ha in the *cerrado*, the Brazilian savannah ([Fearnside 2005](#)). But by 1978 nearly 80 million ha were cleared and during the 1980s the annual loss averaged 1.5 million ha ([Skole and Tucker 1993](#)). Between 1996 and 2005 Amazonia's forest loss of 19.5 million ha progressed into Acre and Amazonas and the government responded by promising substantial deforestation cuts, raising the hopes for eventually ending the destruction ([Nepstad et al. 2009](#)).

Realities have been different: between 1990 and 2015 Brazil's total loss of 15.5 million ha of primary forest remained the world's largest (Morales-Hidalgo et al. 2015) and subsequent policies of the Brazilian government have done little to discourage further destruction. In Haiti the process of deforestation has come almost to its unfortunate end. In 1990 primary forest covered only 4.4% of the country; by 2016 the share was down to 0.32% (Hedges et al. 2018). Haiti may thus become the first small-size country (it is about as large as Albania, larger than Israel) that will completely lose all of its original wet forests. In contrast, forests still cover about 40% of the western part of Hispaniola (the Dominican Republic) and the contrast is clearly seen on satellite images.

China has been a special case. Its mass-scale reforestation campaigns of the Maoist era had largely failed, and by 1980 less than 13% of the country had forests with more than 30% canopy cover (Smil 2004). Subsequent reforestation efforts raised the area to almost 138 million ha in the year 2000 (Liu et al. 2005) but according to the FAO classification, the increase was from 157 million ha in 1990 to 208 million ha in 2015, or to nearly 22% of the country's territory. China's reforestation gain is unmatched by any country but quality has been low. New plantings are largely monocultures of fast-growing pines, poplars, and eucalyptus. Less than 12 million ha (less than 6% of the total) is primary natural forest (for comparison, in 2015 the share of primary growth was 60% in Canada).

The net effect of these changes on the global capacity of forests to act as a major carbon sink has been positive, and it has been potentiated by higher atmospheric CO₂ concentrations and by nitrogen deposition from the emissions generated by fossil fuel combustion (Bellassen and Luyssaert 2014). Between 1990 and 2005 US forests were sequestering every year about 160 Mt of carbon (Woodburry et al. 2007). Forests in Europe (including Russia) have been sequestering 300–600 Mt of carbon a year (Potter et al. 2005; Beer et al. 2006), and every year Chinese forests are storing 190–260 Mt of carbon (Piao et al. 2009). Most importantly, Amazonian forests, whose status as a carbon sink or source was in question, are now seen as major carbon sinks sequestering up to 1.3 Gt of carbon a year (Lewis et al. 2009).

The total annual sink for all of the world's forests averaged 2.4 ± 0.2 Gt of carbon between 1990 and 2007, and with an estimated source of 1.3 ± 0.7 Gt of carbon due to tropical deforestation the net global sink was $1.1 \pm$

0.8 Gt of carbon a year ([Pan et al. 2011](#)). Expanding forests and other vegetation could absorb up to five times as much as they do today—but rising frequency of fires, droughts, storms, and pest infestations could reduce, even eliminate, this flow. Consequently, we cannot be sure if by 2100 forests, and other vegetation, will be net carbon sinks or sources.

Cropland and pastures

All premodern data on the extent of croplands and pastures are just approximations. Even in China, with its relatively rich records, cropland estimates differed by up to 20% as recently as 1900 ([Miao et al. 2016](#)). On the global level the errors around the most likely values are estimated at up to $\pm 25\%$ in 1700 and about $\pm 18\%$ by 1800—but there is little doubt about slow expansion of both of these fundamental land uses during the first 1,500 years of the Common Era, with croplands increasing from about 130 to about 230 million ha and pastures from about 110 to 220 million ha (Klein Goldewijk 2011).

But between 1500 and 1800 cropland area had nearly doubled (230 to 420 million ha) with new farmland opened in Eastern Europe, in central and south China, and in European colonies in Latin America. At the same time, the extent of pastures had more than doubled (from 220 to 510 million ha) with the latter expansion taking place mostly in Asia. As the population growth accelerated, the past two centuries have seen unprecedented change in land use. Global cropland had doubled during the 19th century and the absolute growth of 430 million ha brought the total to 850 million ha, largely due to the westward expansion of North American agriculture on American Great Plains and Canadian Prairies and to similar openings of newly cultivated lands in Australia, Brazil, Argentina, Russian Empire (in Central Asia), and north China.

Pastures expanded even faster during the 19th century, increasing 2.5 times by nearly 800 million ha. Again, this increase was mostly because of the westward progression of settlements in North America and because of the expansion of grazing lands in Australia, sub-Saharan Africa, and Central Asia. The two trends diverged during the 20th century. The growth rate of the global cropland slowed down as the area grew by about 80% but absolute gain was a record of 680 million ha to surpass 1.5 billion ha by the year 2000 and to reach 1.59 billion ha by 2015, thanks to additions on every

continent. Notable gains in Asia included the Soviet expansion of grainlands in Kazakhstan, the US extension of cropping to semi-arid areas in the western Great Plains, conversion of Brazilian *cerrado* (mostly for sugar cane and soybeans) and Argentinian pampa (for soybeans), and new croplands in Australia (mostly wheat) and in sub-Saharan Africa.

Nearly 90% of all cropland is arable land and the rest is under permanent crops (mostly plantations producing fruits, nuts, tea, coffee, and cocoa). But this total both underestimates and exaggerates the area that is actually used for cultivation. Underestimates have two causes. FAO assessments exclude land used for shifting cultivation (still practiced in many regions of Asia, Africa, and Latin America) that has been left fallow for more than five years; and multicropping (planting and harvesting more than one crop every year) is common in most warmer climates and its frequency has been increasing.

Double-cropping accounts for most of the multicropping, and it is practiced in both temperate and subtropical areas. In the United States a third of the double-cropped land is in the Southeast and slightly more than one-fifth in the Midwest, with winter wheat or rye usually followed by corn or soybeans—but in most years the practice has been limited to only about 2% of total cropland ([Borchers et al. 2014](#)). Double-cropping is common in Germany, Poland, and the Eastern European Black Earth regions ([Estel et al. 2016](#)) as well as on the North China Plain, the region that produces nearly half of China's grain ([Jeong et al. 2014](#)). Satellite studies show the share of China's multicropped land at 34% in 2002, with triple-cropping on just over 5% of the total ([Yan 2014](#)). Up to five crops of vegetables can be harvested from intensively cultivated tropical land or under plastic mulch in subtropical areas.

The exaggeration of cropland estimates arises due to large areas of fallow land: that is, cropland that is left uncultivated for a growing season or for an entire year. At the beginning of the 21st century the total area of cropland was 1.6 billion ha (a slightly higher number than the FAO count); fallow area amounted to 442 million ha (28% of the total); cropping intensity was 1.13 when fallow land was excluded, and 0.82 when it gets included; and crop durations (fractions of the year when the land is covered by growing crops) were 0.68 when fallow land was included and 0.49 when it was excluded ([Siebert et al. 2010](#)).

The last ratio means that between 1998 and 2002 the global farmland was cropped about half of the time. For comparison, FAO reported the total harvested area of 1.18 billion ha in the year 2000, a finding that implies an average of 0.77 crop harvests a year. As expected, the highest cropping intensities are in Eastern and Southern Asia (the sequential cultivation of vegetable crops, triple-cropping of Chinese rice), the lowest in sub-Saharan Africa. The cropping ratio is thus much lower than is generally assumed, indicating that further intensification would be possible in order to boost the global harvest, but it would require further energy subsidies and diffusion of appropriate agronomic practices.

Global expansion of pastures set new relative and absolute records during the 20th century as the pastures grew by 2.1 billion ha (nearly 2.7-fold) to the total of just over 3.4 billion ha. Sub-Saharan Africa had the largest absolute gain (more than doubling to about 900 million ha), followed by Latin America (led by Brazil and Argentina), which had quadrupled its total area of pastures ([FAO 2019](#)). FAO's latest global total for permanent meadows and pastures indicates a decline to 3.27 billion ha but the actual area might be significantly smaller: a study that combined inventory data and satellite imagery identified only 2.8 billion ha of grasslands ([Ramankutty et al. 2008](#)). In any case, permanent pastures are the largest area of natural ecosystems that have been modified by human actions to produce food and that area may now be in retreat.

Annual burning of African pastures has been done in order to prevent the incursions of shrubs and trees and to encourage subsequent regrowth. Satellite imagery has shown the dynamics of this process, whose frequency ranges between one and 20 years with about four years being the median interval. As a result, extreme estimates of the annually burned phytomass range are of more than an eightfold range (0.22 vs. 1.85 billion t/year) and the total area burned annually is on the order of 200 million ha, larger than the total of US farmland ([Barbosa et al. 1999](#); [Lehsten et al. 2009](#)).

How far along are we in the transition from undisturbed natural ecosystems to eventual asymptotes of cultivated and grazing land? Growth trajectories of land used for food production form symmetrical logistic curves whose inflection points were in the late 1960s for the growth of pastures and in the mid-1990s for cropland expansion. Asymptotic value for the future expansion of cropland would be about 2.8 billion ha—that is, well below the published assessments of potentially cultivable land: those

assessments were put at between roughly 3.1 and 3.4 billion ha ([Buringh 1977](#); [Smil 2013a](#)). As most of this potentially cultivable land is now covered by forests, wetlands, or grasslands its conversion to cropping would bring further enormous impoverishment of the biosphere.

But it is almost certain that we will not eventually cultivate nearly 3 billion ha of cropland. Post-1950 intensification of cropping prevented conversions of large areas of natural ecosystems to new farmland. In many countries this intensification has actually allowed reducing of cultivated areas despite the combination of continuing population growth. This land-sparing effect has been particularly impressive for those crops that have benefited from the adoption of high-yielding cultivars ([Ausubel et al. 2013](#)). By 2010 land devoted to wheat cultivation in India was to have been nearly four times as large if the yields remained at the 1960 level and the corresponding multiples were to be more than four for the US wheat, about seven for the Chinese corn, and eight for the Chinese rice.

Resulting plateaus and declines of nationally cultivated land have been already substantial. By 2015 cultivated croplands in North America, Europe, and the lands of the former USSR had declined from their peaks reached during the 1950s by, respectively, about 14%, 25%, and 13% ([FAO 2019](#)). America's cropland peaked at about 194 million ha in the early 1950s and it was reduced by 20% to 154.5 million ha by 2016—even after about 36% of grain corn, by far the country's largest crop, has been diverted from animal feed to the fermentation of ethanol for cars ([USDOE 2016](#)). These trends have led [Ausubel et al. \(2013\)](#) to conclude that the global extent of cropland (arable land and permanent crops) that rose from 1.37 billion ha in 1961 to 1.53 billion ha in 2009 has peaked and they projected a return to 1.38 billion ha by 2060.

Since [Ausubel et al. \(2013\)](#) was published, global cropland (according to FAO) has increased further to 1.59 billion ha by 2015, and in 2017 a new global map of croplands (based on satellite monitoring with the resolution of 30 meters) put the total at 1.874 billion ha, with India (179.8 million ha), the United States (167.8), and China (165.2 million ha) in the lead ([GFSAD 2017](#)). At the same time, the notion that the world is approaching the peak extent of cropland is plausible because the increased yields could be achieved not only by further intensification of cropping in Asia and above all in Africa but also, as noted, by reducing the extent of annual fallowing. Combining the two trends would have an even greater land-sparing effect.

On the other hand, extension of cropland in Brazil and in sub-Saharan Africa (to meet food requirements of still rapidly growing populations)—especially when coupled with continued chaotic and insufficiently modernized expansion of African cultivation—could see further growth of cropland for decades to come.

Summarizing the impact

Land cover and land-use changes have changed surface albedo (typically below 0.1 for coniferous forests, as high 0.3 for dry barren soils) and hence soil and vegetation temperatures and the rates of evaporation and evapotranspiration ([Liang et al. 2010](#)). Changed radiation properties brought by replacing natural cover with impervious surfaces have been a major reason for the formation of urban heat islands. They are now present in all large cities and are associated with changes in comfort, wind speed, and precipitation ([Peng et al. 2011](#)). Impervious surfaces have also increased the risk of flooding. Cropping in general, and poor agronomic practices in particular, have increased the mobilization of terrigenous dust, the rates of soil erosion, sediment removal, and losses of organic matter from lowering the retention of soil moisture ([Wilkinson and McElroy 2007](#); [Eglin et al. 2010](#)).

In 2015 the grand total of altered forests, pastures, cropland, and urban areas added about 7.5 billion ha of land whose cover was destroyed, replaced, or modified by humans, an equivalent of 55% of the planet's non-glaciated land. But this total excludes land whose natural cover was destroyed or replaced by all forms of mining, nonurban settlements and industries, transportation corridors, and water reservoirs. Estimates for these impacts were published by [Hooke et al. \(2012\)](#) and [Smil \(2015b\)](#). The first category includes extraction and processing of minerals and fossil fuels: pits, quarries, and open-cast mines have obviously the largest impact but many underground mines leave considerable surface footprints because of the disposal of mining and processing wastes.

By 2015 the total affected area was on the order of 50 million ha. The area taken by rural housing is at least as large as the urban total (200 million ha); all roads and railways (including the adjacent strips of land) add no less than 500 million ha. At the same time, settlements and many transportation corridors have preserved some remnants of original land cover and they

include often extensive areas of newly planted grasses, shrubs, and trees in parks, along roads and highways, and around suburban housing. The worldwide area of water reservoirs now exceeds 200 million ha and I estimated the total area of rights of way for pipelines and high-voltage lines at about 100 million ha (they may be planted by grasses, shrubs, or small trees).

The grand total of land affected by human action is about 8.5 billion ha, or about 63% of all ice-free land. [Hooke et al. \(2012\)](#) also added at least 500 (and possibly more than 700) million ha modified by deposition of eroded sediment that originates from human activities, including runoff from mining, dust raised by plowing, and other human activities and accelerated erosion due to construction, crop cultivation, deforestation, overgrazing, and desertification. The medium estimate of this anthropogenic deposition would raise the grand total of areas affected by human actions to about 9 billion ha, or 67% of all non-glaciated land. Two-thirds of ice-free land has now been affected, with various intensities, by human activity: we have become an unrivaled terraforming species. But specific global land uses are finite, and it is most likely that we will reach many of their peak levels before the end of the 21st century.

The role of humans as geologic, terraforming agents can be also illustrated by estimating masses rather than areas involved. British geologist Robert Lionel Sherlock was the first scientist to call attention to this process by his detailed inventory of materials mobilized by human actions in Great Britain ([Sherlock 1922](#)). He calculated that between 1500 and 1914 excavations associated with mining, quarrying, railway, roads, canals, and port construction and with the expansion of cities amounted to more than 30 billion m³ of material, an equivalent of removing a layer nearly 10 cm thick from the surface of the British Isles. When humanity was compared to a natural geomorphic force of denudation, he concluded, “in a densely developed country like England, Man is many times more powerful, as an agent of denudation, than all the atmospheric denuding forces combined” ([Sherlock 1922](#), 333).

[Wilkinson \(2005\)](#) made an attempt to express this removal of rocks and sediment by viewing it in a deep-time perspective. He found that during the past half a billion years natural denudation processes lowered continental surfaces by a few tens of meter per million years while modern construction and food production have been transporting sediment and rock at rates that

would imply lowering all of the Earth's non-glaciated surfaces by a few hundred meters per million year. Anthropogenic denudation now runs an order of magnitude faster than the global Phanerozoic mean—but, obviously, no civilization could keep denuding the planet at such a rate and survive for millions of years. Recent reports about shortages of sand required for land reclamation and for construction concrete are just the most notable aspect of this process. Wilkinson's reconstruction also indicates that humans had already become the leading agents of erosion before the end of the first millennium of the Common Era but most of the anthropogenic denudation has taken place since 1800.

Other recent studies of global land cover and land use confirm the extent of human intervention. So far, the most complete, and also the most accurate, assessment of the global land cover is FAO's GLC-SHARE, released in 2014 ([Latham et al. 2014](#)). The analysis, based on a variety of datasets and including all snow-covered areas, glaciers, and Antarctica (altogether 9.7% of all continents), put artificial surfaces at just 0.6% of total continental area, cropland at 12.6%, grassland (together with shrubs and herbaceous and sparse vegetation) at 31.5%, tree-covered areas at 27.7%, bare soil at 15.2%, and water bodies and mangroves at 2.7%. After subtraction of the share of primary forests this finding would indicate that at least 63% of all surfaces (including the glaciated land) have been affected by human action—but the classification used by the authors makes it clear that the actual area is somewhat larger, as it gives no indication about the extent of the impact on barren surfaces and coastal ecosystems.

A broader approach to anthropogenic land-use changes is to use satellite monitoring (with 1 km² resolution) to construct human footprint maps that indicate the cumulative impact of direct pressures exerted by human activities. The definition of human footprint developed by [Venter et al. \(2016\)](#) includes eight inputs: the areas of built environments, cropland, and pastures; human population density; nighttime lights; and railways, roads, and navigable waterways. Continuous monitoring shows that between 1993 and 2009 the overall human footprint score increased by less than 9% even as the human population grew by 23% and the global economic output expanded by 153%. In total, about 75% of the planet was experiencing measurable human pressures in 2009, and the previous 16 years had seen the largest relative increases for the built environment (about 11%), croplands (21%), and night lights (24%). High-resolution maps—available

at <https://wchumanfootprint.org/>—make it possible to trace the progress of human impacts and to identify the areas of lessening and rising pressure, the former concentrated in the US Midwest, the Canadian Prairies, and parts of Europe and Southeast Africa, the latter most prominent in Brazil, Sahel, India, Indonesia, China, and parts of Ukraine and Russia.

We can also ask the opposite question: how much of the Earth's surface remains a wilderness. The term does not refer to the absence of any significant biophysical disturbances, the quality that is often a function of remoteness from settlements and infrastructures (Kormos et al. 2017). Of course, even remote and isolated areas might have been subtly modified by atmospheric deposition of sulfates and nitrates from faraway sources as well as by the rising concentrations of CO₂. And there is nothing new in finding how widespread the human reach has been: historic examples of surprisingly intrusive impacts range from the discovery of the Amazon's *terra preta* to Jean-Jacques Rousseau's *Reveries of a Solitary Walker* (Rousseau 1782).

The Brazilian Amazon was seen as a prime example of undisturbed natural forest—until the discoveries of *terra preta de índio* (Indians' black earth), areas of ancient anthropogenic soils throughout the basin (Sombroek 1966; Lehmann et al. 2003). These carbon-rich soils, created by pre-Colombian societies, occur in patches averaging about 20 ha but they cover thousands of square kilometers and they are enriched with charcoal from cooking fires and with organic matter from kitchen middens that were deposited by now extinct populous and stratified societies, with some settlements growing to urban scale (Roosevelt 2013). Their activities had also left behind wetland fields, secondary forests, earth mounds, and signs of widespread shifting agriculture.

And nothing captures better the surprising extent of human intervention than Rousseau's experience with wilderness. During his walk deep into an Alpine ravine he arrived

at a retreat so hidden that I have never seen a more desolate sight in my life. . . . I compared myself to those great travelers who discover an uninhabited island, and I said myself with self-satisfaction: "Without a doubt, I am the first mortal to have penetrated thus far" . . . While I preened myself with this idea, I heard, not far from me, a certain clanking. . . . I got up, burst through a thicket of brush . . . and, in a little hollow twenty feet from the very place where I believed myself to have been the first to arrive, I saw stocking mill (Rousseau 1782, 100).

Rousseau's reaction was a mixture of relief ("to find myself back among humans when I had believed to be totally alone") and dismay ("being unable, even in the deepest recesses of the Alps, to escape from the cruel hands of men").

The first reconnaissance-level inventory of the remaining global wilderness—identified as contiguous areas of natural land cover larger than 400,000 ha (that is, at a minimum, equivalent to a square with a side of about 63 km)—was done during the 1980s. [McCloskey and Spalding \(1989\)](#) found that during that decade about a third of all continental surfaces, an area totaling 4.8 billion ha and comprising more than 1,000 tracts, was still in that state. Shares of wilderness ranged from 100% in Antarctica and 65% for Canada to less than 2% in Mexico and Nigeria, and except for Sweden no such areas were found even in the largest European countries. Antarctica aside, boreal forests and circumpolar cold deserts remained least affected while temperate forests of the Mediterranean, eastern North America, and China, and tropical rain forests of the Guinean Highlands, Madagascar, Java, and Sumatra had no remains of large contiguous wilderness.

Subsequently the loss of wilderness accelerated, and between 1993 and 2009 330 million ha of it, an area larger than India, was lost to human activities ([Watson et al. 2018](#)). Only about 23% of land outside Antarctica can be classed as wilderness with just five countries holding more than 70% of that area (in boreal forests of Russia, Canada, and the United States, in Brazil's rain forest, and in the Australian desert), and 20 countries containing 94% of the total. A similar inventory of intact ocean ecosystems (if we take into account 15 current anthropogenic stressors as well as their low combined cumulative impact) has shown an even higher degree of disruption ([Jones et al. 2018](#)). Only 13.2% of the world's ocean was classified as marine wilderness. Coastal waters, including coral reefs, account for just 10% of the remaining wilderness whose extensive remains are now found only in the western tropical Pacific and in the Southern Ocean.

Another constraint on further conversions of the remaining natural ecosystems has been the increasing extent of areas protected in reserves and wilderness parks. By 2016 the world had 202,467 protected areas extending over almost 20 million km², or nearly 15% of continental area and close to the target of 17% set for 2020 (IUCN 2016). There are now 238 large

conservation areas (including Yellowstone National Park, the Okavango Delta, and the Galapagos Islands) that belong to Natural World Heritage sites and that account for 8% of the total protected area ([Kormos et al. 2017](#)). Protection of marine biota is much less extensive. As already noted, only about 13% of the ocean can be classified as marine wilderness but only about 5% of that area is currently protected by various exclusion zones ([Jones et al. 2018](#)).

Environmental Degradations

Nearly all changes affecting land cover and land use involve environmental degradations (deforestation reduces biodiversity, intensive farming accelerates soil erosion, impermeable surfaces help to create urban heat islands) but I have bundled them separately because they are primarily defined by the changing areal extent. In contrast, the diverse category of environmental degradations shares the commonality of a qualitative loss. Modern societies have subjected the biosphere to so many insults—ranging from the millennia-old mismanagement of arable soils to the residues of pesticides and medicines that remain present even in treated water ([Schröder et al. 2016](#)) and microplastic pollution in the ocean ([Zarfl et al. 2011](#))—that I must limit my attention only to the most consequential degradative changes. Most of them fit into two broad categories of qualitative transformations and environmental pollution (the introduction of undesirable anthropogenic materials or mobilization of naturally occurring compounds with the potential for harm).

Concerns about physical shortages of existentially fundamental (and obviously finite) natural resources are much less important than concerns about their qualitative changes. As already explained, we are fallowing large shares of available cropland and wasting indefensibly large shares of food production—and hence there should be no globally justifiable concern about running out of farmland. Wood for timber and paper can be successfully harvested from tree plantations, engineered lumber can be made from what was formerly waste woody phytomass, and other construction materials (concrete, steel, aluminum, glass) make excellent substitutes—and hence we are not facing any worrisome wood shortages. Water has been undoubtedly the most mismanaged critical resource yet

even in this case we have enormous opportunities to manage its use much more rationally by better pricing, by universal recycling and, given that agriculture is by far the largest consumer, by optimizing the choice of crops grown and animals raised for meat.

Qualitative changes

In contrast, many qualitative transformations that have resulted from human actions are difficult, or outright impossible, to remedy. For example, it is hard to imagine that wild elephants will return to Tunisia, Algeria, and Morocco, all part of their original range. And while a small amount of cod can still be caught on the banks of Newfoundland, the species failed to make any large-scale comeback nearly 40 years after imposing a moratorium on its commercial fishing, and it survives reduced to a tiny fraction of its natural abundance that was the basis of a fishery that lasted nearly half a millennium ([Haedrich and Hamilton 2000](#)).

Loss of biodiversity is a phrase that is too academic, too sanitary to convey our disregard for other species with which we share the biosphere. Not surprisingly, a great deal of attention has been given to modern extinctions (or near-extinction) of once-abundant species, including the American passenger pigeon and the bison (still common sights in 1860, gone, or nearly so, by 1890), and modern concerns about biodiversity are publicized by using such charismatic animals as pandas, tigers, and whales. But two kinds of decline have been much more important: those of commercially important species harvested for food in the wild, and the broadly based reductions of many mammalian groups, a process whose consequences cannot be remedied on a civilizational time scale.

The first kind of impoverishment is most evident, and nutritionally and economically most consequential, in the over-harvesting of fish and marine invertebrates. While the anthropogenic defaunaation on land has a long history and was a factor in the extinction of the Pleistocene megafauna, oceanic defaunaation began to intensify only with the adoption of industrial fishing ([McCauley et al. 2015](#)). This aggressive capture began during the late 19th century as steam-powered ships could deploy much larger nets than those used by sailing vessels and could also fish by continuous trawling, dragging large nets across the sea bottom.

The post-WWI adoption of diesel engines further increased the average power and operating range of motorized fishing, and this trend was completed after World War II with the introduction of large factory ships (with on-board processing and refrigeration) that could easily reach remote fisheries (including the Antarctic waters), locate fish with sonar, and use long (up to 50 km) drift nets. Similarly, modern whaling with harpoon guns on diesel-powered vessels was much more destructive than the traditional hunt using boats launched from sail ships, and only the 1982 ban on commercial whaling saved the largest species from near-extinction ([Kalland and Moeran 1992](#)).

Modern industrial fishing has brought a threefold expansion of fisheries, farther from ports, deeper into demersal waters, and harvesting previously untouched taxa ([Pauly 2009](#)). Between 1950 and 2000 this vacuuming of oceans reduced the predator species density by half in both the Atlantic and Indian Oceans and by about 25% in the Pacific ([Worm et al. 2005](#)). By the beginning of the 21st century commercial fishing had reduced the biomass of large demersal and pelagic species (cod, tuna) by at least an order of magnitude ([Pauly 2009](#)). FAO's global assessment of fish stocks found that by 2009 about 57% of them were fully exploited (at or very close to sustainable maxima), 30% were already overexploited, and only 13% were not fully exploited—but most of the latter stocks have limited potential for harvest expansion ([FAO 2011](#)).

An automatic identification system (originally designed to prevent ship collision) now allows the tracking of more than 70,000 industrial fishing vessels, and after processing 22 billion positions, [Kroodsma et al. \(2018\)](#) were able to map (with accuracy two to three orders of magnitude higher than in previous attempts) the global footprint of fishing from 2012 to 2016. They found that industrial fishing takes place in more than 55% of the world's ocean, in an area more than four times as extensive as agriculture. As expected, total fishing efforts (hours fished per unit area) are highest in the coastal waters of Europe, East Asia, and the North Pacific (latitudinally the highest global intensity is between 45° and 50° N) but high-intensity fishing also goes in large parts of the equatorial Pacific Ocean, while circum-Antarctic waters are not fished heavily.

Loss of marine biodiversity is impairing the ocean's food production capacity, affects water quality, and makes it more difficult to recover from perturbations ([Worm et al. 2006](#)). Price is a good indicator of increasing

scarcity, and the highly endangered bluefin tuna (*Thunnus thynnus*, Japanese *maguro* prized for *sushi* and *sashimi*) is the best example of the general trend affecting the cost of wild fish. Japanese prices (all per kg) rose from about \$0.1 in the late 1960s to about \$2.5 in 1975 and in October 2018 the average price of fresh tuna at the Toyosu wholesale market was \$53 (Buck 1995; TMG 2019)—that is, a more than 500-fold rise in 50 years.

Not surprisingly, overfishing has led to a rapid expansion of aquaculture. This ancient practice has grown to a global industry whose annual output (inland and marine) reached 80 Mt in 2016, compared to about 91 Mt of captured marine and freshwater species (FAO 2018b). Aquaculture now produces such commercially desirable carnivorous species as salmon, sea bream, and even tuna (Benetti et al. 2016). Raising herbivorous species can be done by using plant feed formulated for optimal growth but producing carnivorous fish requires an adequate supply of fish protein, and for some species also of fish oil, and these needs can be met only by harvesting such species as anchovies, sardines, herring, and capelin in order to prepare fish meals and oils (Hasan and Halwart 2009). Aquaculture thus eases as well as intensifies the pressure on wild marine species.

On land the new world of cities and megacities has created large areas where animal zoomass is dominated by dogs and cats and where the only thriving wild mammals and birds are mostly such global invaders as rats, pigeons, and crows, joined regionally by a few other species, including raccoons and deer, and hence also coyotes (in large parts of North America) and monkeys (resus macaques, grey langurs) in India. There are many ways to illustrate this terrestrial defaunation, but perhaps the most misleading (and certainly most misunderstood) way to document the retreat of animal populations is to simplify the finding of the latest World Wildlife Fund *Living Planet Report* (WWF 2018b) and to claim that since 1970 the planet has lost 60% of all animals.

The Fund's biennial Living Planet Index (LPI) combines all available species-abundance data, and its latest iteration found that populations of vertebrates declined, on average, by 60% since 1970. Obviously, the outcome is heavily influenced by further absolute losses of animals whose populations have been already much reduced: the loss of 20 rhinos may mean that their particular isolated population is down by 90%, the loss of 10,000 Canada geese makes a negligible dent to their enormous population. A less confusing metric of this loss is what the International Union for

Conservation of Nature calls its barometer of life, its Red List of threatened species.

So far, the Union has assessed more than 96,000 species (with complete coverage for mammals, birds, amphibians, and some marine animals), of which more than 26,500 are threatened with extinction. Specific shares are 40% of all amphibians, 33% of reef-building corals, 25% of mammals, and 14% of birds (IUCN 2018). According to [Dirzo et al. \(2014\)](#), 322 species of terrestrial vertebrates have become extinct since 1500, with the remaining species declining by an average of 25% since then. Some invertebrates may have fared even worse, with some studies reporting large declines in the abundance of insects in general ([Hallmann et al. 2017](#); [Lister and Garcia 2018](#); [Sánchez-Bayo and Wyckhuys 2019](#)) and butterflies in particular ([Habel et al. 2015](#); [Stenoien et al. 2017](#)). The main causes of these declines are habitat loss, pollution, pathogens, and introduced species and climate change.

Yet another way to gauge the loss is by estimating the time that would be required for global diversity to recover to a pre-anthropogenic state. [Davis et al. \(2018\)](#) used a birth–death tree framework to demonstrate that even if today’s extinction rates were to decelerate to pre-anthropogenic levels the recovery of lost mammalian phylogenetic diversity would most likely take millions of years. But even hoping for such a deceleration is misplaced: [Butchart et al. \(2010\)](#) assessed long-term trends of global biodiversity loss and concluded that, despite some local successes, the overall rate of loss was not slowing.

Environmental interference includes a large variety of undesirable additions and interventions that affect normal biophysical properties and functions. Loss of darkness has been one of the most consequential interferences. While temperature and precipitation regimes have seen considerable changes on the evolutionary time scale, natural light at a given latitude has been constant and its disruption by artificial lights is a new and a potentially significant interference in this key cycle ([Gaston et al. 2013](#)). All organisms have evolved with strong circadian rhythm regulated by day/night sequences that have now been compromised not only indoors but also by extensive outdoor lighting. Light pollution also affects primary productivity, repair, and recovery of some physiological functions and, obviously, visual perception and spatial orientation of organisms and hence the navigation of highly mobile species.

Nighttime exposure to light affects the production of melatonin in humans. This hormone, whose flow is governed by the circadian rhythm, not only induces sleep but it also improves immunity, lowers cholesterol, and affects all glands ([Wright and Lack 2001](#)). The problem has been made much worse by evening or late-night exposure to electronic screens and to other light sources whose spectrum is shifted toward blue light ([Oh et al. 2015](#)). Links have been also suggested between excessive light exposure and the incidence of cancer, diabetes, and cardiovascular disease. Experimental research also raised the possibility that light at night increases body mass by shifting the time of food intake ([Fonken et al. 2010](#)).

This trend will only get worse with the unfolding mass-scale transition toward LEDs: although they are more efficacious than other light their spectrum has a pronounced spike at the wavelength (470 nm, blue light) that is the most effective suppressor of melatonin during the night ([Wright and Lack 2001](#); [Oh et al. 2015](#); [Kraus 2016](#)). These concerns have to be balanced by the fact that the common assumptions about recent declines in sleep duration are not supported by the best available analyses. [Hoyos et al. \(2015\)](#) concluded that there is little evidence for the claimed epidemic of declining sleep in 12 countries, and [Youngstedt et al. \(2016\)](#) came to a similar conclusion after comparing American data from 1960–1989 with those for 1990–2013.

Urban inhabitants and animals also experience acoustic interference due to relatively high background noise, and structural interference in bird flight has been a source of large-scale mortality because birds generally do not perceive clear or reflective glass as an obstacle and are also often attracted to well-lit facades ([Klem and Saenger 2013](#)). Migrating birds—particularly after crossing from water to land, and urban birds disoriented by large sun-reflecting surfaces of glassy skyscrapers—collide with these walls, often at speeds that cause instant death or serious injury. But more than half of all deadly collisions are with low-rise buildings and the estimates of annual death toll are, expectedly, uncertain: for the United States they range between 365 and 988 million birds ([Loss et al. 2014](#)). For feeding or migrating mammals, amphibians, and crustaceans the interference comes in the form of freeways and canals, while large dams (unless equipped with special runs) present insurmountable obstacles to anadromous fish returning to their breeding grounds (on the assumption that they make it downstream over spillways or through turbines).

Large dams (higher than 15 m) are another perfect example of a global-scale interference. They have been built on every continent for electricity generation or for multiple uses, including water supply for cities and irrigation. Their total has surpassed 57,000 and by 2014 there were at least an additional 3,700 structures planned or under construction ([Zarfl et al. 2014](#)). The world's largest dams are the most massive accumulations of reinforced concrete and create reservoirs whose areas are of a similar order of magnitude as that of some small countries ([Smil 2015b](#)).

Construction of large dams has displaced at least 40 million people (mostly in China and India), and interrupted flow and mass-scale storage of water behind the dams has a number of important effects on eventual releases downstream. Reservoirs trap large shares of transported silt, depriving the downstream areas of this nutrient-rich material while storing it behind dams and hence shortening the reservoirs' useful lifetimes; stored water is aged before its eventual release; and while the temperature of river water has a large seasonal amplitude, the temperature of water released from deep reservoirs has a minimal annual variability. And large areas of stagnant and often nutrient-enriched water create ideal conditions for the growth of algae and other invasive aquatic plants.

At the end of the 20th century water stored behind large dams represented a 700% increase in the standing stock of natural river water. Reservoir-induced aging of impounded water exceeded three months at the mouths of several large rivers, with the global mean tripling to well over one month (Vörösmarty et al. 1997). Obviously, water aging changes net flow balance and regime, it affects reoxygenation of surface layers and sediment transport. In temperate regions water released from large and deep reservoirs in summer is significantly colder than in a free-flowing stream, often cold enough to disrupt biota. In warmer climates nutrient-rich reservoir water becomes a perfect place for algal growth that may expand into offensive blooms. Excessive silting of reservoirs has been common throughout monsoonal Asia and particularly in some regions of China, where the useful volume of water storage has been in some cases reduced below the design expectations in a matter of decades ([Smil 2004](#)).

Invasive species have become common in the global economy. Kudzu vine smothering even large trees or cane toads crushed on highways are well-known examples. Kudzu is a perennial subtropical Asian vine that was introduced to the United States in 1876, and that now covers some three

million ha in the southeastern United States, extends as far north as Nova Scotia, and defies eradication efforts ([Webster et al. 2007](#)). Cane toads, large South American poisonous amphibians introduced to Queensland in 1935 in order to control cane beetles, have been expanding their range by up to 60 km/year and by 2009 they crossed the border of Western Australia and Northern Territory, more than 2,000 km from the site of their original release (DPW 2014).

Chestnut blight fungus (*Cryphonectria parasitica*), introduced at the beginning of the 20th century, destroyed the American chestnut, a large and dominant tree of Eastern American forests ([Freinkel 2007](#)). Asian ascomycete fungus (*Ophiostoma*) arrived in the eastern United States first in 1928 via Europe, and it has destroyed most of American elms (*Ulmus americana*) as far west as Saskatchewan ([Hubbes 1999](#)). And the third Asian invader is woolly adelgid, a small sap-sucking insect (*Adelges tsugae*) now destroying North American hemlocks, *Tsuga canadensis* and *Tsuga caroliniana* ([Nuckolls et al. 2009](#)). Eradication of invaders is costly, usually exceedingly difficult, and often impossible. The first complete success was achieved in 2005 on the Campbell Island in New Zealand's sub-Antarctic (Department of Conservation 2019) and was followed by the deratization of Macquarie Island south of Campbell Island (completed in 2010), islands in the Aleutians and Galapagos groups, and, the largest of all, South Georgia Island in the South Atlantic.

Environmental pollution

Premodern environmental pollution was common, often serious, but nearly always spatially restricted. In the countryside the most common form of pollution with chronic health consequences was burning of wood in unvented or poorly vented rooms. This practice still causes, and aggravates, respiratory diseases in rural areas of low-income countries in Africa and Asia ([WHO 2018b](#)). Traditional animal husbandry also exposed villagers to runoff from barns and open dung heaps, and entire settlements had to live with open sewers and with recurrently polluted water wells.

The rise of environmental pollution was closely associated with industrialization and urbanization. Urban water pollution became more common as industries mingled with housing and as once-through water supplies simply discarded contaminated flows. Combustion of coal became

the leading source of air pollution. Today's cities offer diverse combinations of worsening and improving trends: almost always water is piped in, human waste is flushed away (reducing the risks of water-borne infections), and basic water treatment is now (almost) standard, but garbage removal may be sketchy, recycling is almost nonexistent (as mountains of commingled refuse pile up on city outskirts), and air pollution often reaches unprecedented levels (with concentrations of small particulates being often an order of magnitude above the hygienic maxima), as does noise and light pollution.

Visible air pollution (ash, soot) and invisible particulates were the most obvious markers of coal-based modernization as they blackened structures and reduced visibility, and still interfere with photosynthesis and cause respiratory illnesses. The impact of particulates on vegetation, health, and visibility is potentiated by the presence of sulfur oxides, and beginning in the closing decades of the 19th century the resulting smog became a common occurrence in large industrialized cities. Its most acute incidence, London's worst smog episode in December 1952, when heavy particulate and sulfurous air pollution caused 4,000 premature deaths, led to the adoption of the Clean Air Act, the first comprehensive legislation to clean a country's air, in 1954 ([Brimblecombe 1987](#)). Controlling this classic (particulate and SO₂) smog in Western cities took a few decades: New York City had its last serious episode between November 19 and 25 in 1966 ([Fensterstock and Fankhauser 1968](#)).

Sulfur and nitrogen oxides emitted from tall stacks of electricity-generating plants, smelters, and other industrial enterprises were carried over long distances downwind and converted by atmospheric reactions to sulfates and nitrate. Generation of these acidifying compounds was made easier by the widespread post-1950 installation of electrostatic precipitators that removed more than 99% of all fly ash, whose alkaline components might have neutralized some of those emissions. Sulfates and nitrates are fine (0.1–1μ) aerosols that scatter light and reduce visibility, and their eventual deposition acidifies lakes and agricultural and forest soils. Because their deposition commonly took place hundreds of km downwind from the emission sources, the problem assumed semi-continental dimensions, as it affected most of Eastern North America and Northwestern, Central, and Northern Europe ([Smil 1997](#)). But catastrophic scenarios of highly acidified

lakes and dead forests, offered as recently as the mid-1980s, never materialized.

Use of low-sulfur coal, substitution of coal by natural gas (whose combustion releases no particulates and no sulfur oxides), and large-scale desulfurization of flue gases emitted by electricity generation stations were the main ingredients of the eventual solution. Desulfurization and a shift to natural gas were also the main reasons that acid deposition (commonly known as acid rain) was transformed from the leading environmental problem of the 1970s and 1980s into a footnote in the history of environmental pollution ([Smil 2013d](#)). By the time China began its unprecedented expansion of coal-fired electricity generation, flue gas desulfurization was a mature technique that helped to limit Chinese emissions; moreover, terrigenous alkaline dust from North China's loess and desert areas has been a significant airborne buffer.

Photochemical smog, a new air-pollution phenomenon, was first noted in the Los Angeles basin during the closing years of World War II. [Haagen-Smit \(1952\)](#) explained its complex origins. When the primary emissions of carbon monoxide, nitrogen oxide, and volatile organic compounds—produced mainly from the combustion of hydrocarbons in cars and industries and from evaporation of fuels and solvents—undergo a series of photochemical reactions they are transformed into secondary pollutants with ozone and peroxyacetyl nitrate (PAN) as their most unwelcome components. Ozone, an essential stratospheric shield against ultraviolet radiation, is an aggressive compound near the ground, damaging lungs, plants, and materials. PAN is also a major respiratory and eye irritant, while NO₂ is largely responsible for the brownish coloration of smoggy air that is now encountered in summer in all megacities, and that is nearly a chronic occurrence in sunny climates.

Industrializing cities first got underground sewers (returning to designs pioneered by the Romans), and then they eventually ceased dumping raw sewage into streams, lakes, and coastal waters and installed basic modern water treatment ([Spellman 2003](#)). In some European and North American cities their construction began before 1900 and intensified before World War II; in Japan they arrived only during the 1950s and in China a generation later, while sewage treatment in Lagos, Nigeria's largest city, remains grossly inadequate ([Asemota et al. 2011](#)). Wastewater treatment ranges from the simplest primary process (sedimentation and separation of

heavy and floating solids) to secondary treatment (removal of suspended and dissolved matter) and to the most expensive, tertiary treatment, which removes nitrogenous and phosphorous compounds and disinfects the effluent.

New categories of water pollution range from microplastics to potentially harmful residues. Perhaps the best example in the latter category is a growing use of pharmaceuticals and the absence of commercially available cost-effective treatments to remove their residues from wastewater. Municipal effluents, and the receiving water bodies, now commonly contain traces of such recalcitrant drugs as the painkiller diclofenac and the hormones 17β -estradiol and 17α -ethinylestradiol (Schröder et al. 2016). Inadequate information is also available about long-term effects of low but ubiquitous concentrations of these, and other, pharmaceuticals and their metabolites (Touraud et al. 2011).

Other concerns

Perhaps the most consequential among many other concerns is the bacterial resistance to antibiotics. This development, coupled with the slow advances in putting new antibacterial drugs on the market, is a major threat to global health and food security (WHO 2018c). Accumulation of plastic waste in the ocean might be the visually most off-putting phenomenon but the images of this new wave of durable, floating garbage covering coastal waters and being deposited on beaches convey only part of the problems, as they cannot portray the vastly more numerous (and more harmful) microplastics. And the human enrichment of natural flows of nitrogen and phosphorus is certainly among the least publicly discussed anthropogenic degradations of the biosphere.

Few 20th-century inventions brought benefits comparable to the use of antibacterial drugs, which have nearly eliminated death due to previously untreatable diseases. But the inevitable bacterial adaptations were noted almost immediately (Ventola 2015). The first penicillin-resistant *Staphylococcus aureus* was found as soon as 1947, and the subsequent reliance on methicillin led to the emergence of methicillin-resistant strains of *Staphylococcus aureus* (MRSA) by 1962. Various MRSA strains are now encountered worldwide, particularly in hospitals, where they cause most nosocomial infections (Hassoun et al. 2017). Vancomycin became the drug

of last resort—and the first vancomycin-resistant bacteria appeared by 1986 (Leeb 2004).

Diffusion of antibiotic-resistant strains can be traced to overprescribing of antibacterials by doctors and veterinarians; to excessive self-medication in countries where some of those drugs are available without prescription or by users who buy them on the Internet (Mainous et al. 2009); to poor sanitation in hospitals; and to large-scale prophylactic use of antibacterials in meat, egg, and milk production. Resistance to common antibiotics is now present in some wild animal species, and antibiotic-resistant genes were found in tropical and temperate soils as well as in the Arctic (Clare et al. 2019). Increased mortality, prolonged hospital stays, and higher medical costs would be minor consequences compared to a widespread loss of antibiotic efficacy. In that new-old post-antibiotic world, annual flu epidemics would result in many more deaths due to complications with bacterial pneumonia, and tuberculosis and typhoid fever would be, once again, dreaded diseases without effective cures.

Many bacterial strains have now acquired multiple resistance to all commonly used antimicrobials. Their list includes such common pathogens as *Escherichia coli* (gastroenteritis, urinary tract infections), *Haemophilus influenzae* (pneumonia, meningitis, and ear infections), *Mycobacterium* (tuberculosis), *Salmonella typhi* (typhoid fever), *Shigella dysenteriae* (severe diarrhea), and *Vibrio cholerae*. As a result, a growing number of common infections, including pneumonia, tuberculosis, gonorrhea, and salmonellosis, are harder to defeat as the first or even the second choice of antibiotics that have been used to treat them have become less effective.

Domestic animals receive about 80% of all produced antibiotics (to prevent infections in CAFO and for growth promotion) and hence it is not surprising that residues of fluoroquinolones, sulfonamides, and tetracyclines are commonly present in poultry litter and in cattle and swine manure, and that the storage and application of these waste fosters antibiotic resistance (Van Boeckel et al. 2015; CDDEP 2015). Preventing their entry into the environment is difficult: Van Epps and Blane (2016) found that active management of compost piles did not accelerate antibiotic degradation and that anaerobic digestion was not effective to neutralize some key antibiotic residues.

An entirely new set of environmental problems has been created by the introduction of synthetic materials. Nitrocellulose-based Parkesine was

introduced in 1862 but the age of plastics began only during the early 20th century with Bakelite and polyvinylchloride, and most of the commonly used synthetics (polystyrene, Plexiglass, nylon, polyethylene, Teflon, and urea formaldehyde) were invented only during the 1930s and began to make their commercial impact after World War II ([Smil 2005](#); [Zalasiewicz et al. 2016](#)). The subsequent rise of production was exponential as plastics replaced metals, glass, and ceramics in countless industrial, transportation, and household applications.

Worldwide production of plastics rose from 2 Mt in 1950 to 380 Mt in 2015 and the cumulative 1950–2015 output was 7.8 Gt ([Geyer et al. 2017](#)). By 2015 about 6.3 Gt of that total was no longer in use and of that total 12% were incinerated and just 9% were recycled, leaving 79% as waste jamming landfills, burdening soils, accumulating on land, entering fresh waters, and getting into the ocean, which receives considerably more plastic than would be indicated by estimates of the floating debris. Plastics incorporated into durable products (furniture, machinery) can be in use for decades; plastics for packaging are often discarded immediately after a single brief use.

The best US account shows that in 2015 only about 9% of plastic produced in that year were recycled, 16% were burned, and 75% were landfilled, creating long-lasting anthropogenic sediments (USEPA 2018; [Zalasiewicz et al. 2016](#)). [Jambeck et al. \(2015\)](#) calculated that in 2010 some 275 Mt of plastic waste were generated in 192 coastal countries and that between 4.8 and 12.7 Mt entered the ocean. China is the largest offender with up to 3.5 Mt plastics dumped in a year, compared to no more than 0.11 Mt for the United States. Indonesia is a distant second, followed by the Philippines and Vietnam. Oceans receive plastic both from the waste originating on land and from deliberately discarded or lost fishing gear (including massive ghost nets).

Most varieties of plastic persist in the environment and as about 60% of these synthetics are less dense than seawater, that plastic waste floats and, driven by currents, it eventually accumulates in remote areas of the world's oceans, clogging shore waters and washing on the beaches. [Lebreton et al. \(2018\)](#) attempted to quantify what is perhaps the largest ocean plastic accumulation in subtropical waters between California and Hawaii, known as the Great Pacific Garbage Patch (GPGP). Their result, calibrated with data from ships and airborne surveys, put the floating total at 79,000

(45,000–129,000) t inside an area of 1.6 million km²: that is, a 4–16 times larger mass than previously reported. More than 75% of it is debris larger than 5 cm, fishing nets were nearly half of that total, and microplastics were 8% of the total mass but 94% of the estimated 1.8 (1.1–3.6) trillion floating pieces. These reports received widespread attention, but the highest concentrations of microplastics may be actually present in deep pelagic waters at depths between 200 and 600 m ([Choy et al. 2019](#)).

Microplastics are also common in fresh waters (including the plastic microbeads from personal-care products and fibers separated during the laundering of synthetic fabrics) and on land, either through the application of sewage sludge or (as already noted in [Chapter 3](#)) after weathering and disintegration of protective plastic sheeting used in crop production when different size of torn materials become surface litter or soil contaminant ([Rochman 2018](#)). Plastics are already dispersed in sedimentary deposits, and once the landfills, their most concentrated sites, have eroded they will eventually enter the sedimentary cycle ([Zalasiewicz et al. 2016](#)).

Anthropogenic changes of the nitrogen and phosphorus cycle have received only minor public attention compared to the human interest in the global carbon cycle. But no other biogeochemical cycles have been affected by our actions to such an extent as the cycling of these two elements. Modern societies produce reactive nitrogen mainly by the Haber-Bosch fixation and the global output of fixed ammonia reached 166.4 Mt N in 2017, with 113.6 Mt N (nearly 70%) of the latter total used as fertilizer, with the rest used by chemical industries ([FAO 2017b](#)). Cultivation of leguminous crops (led by soybeans and alfalfa) adds about 50 Mt N/year, and nitrogen oxides, equivalent to about 30 Mt N/year, are released by high-temperature combustion of fossil fuels in electricity-generating plants and by internal combustion engines. This release adds up to nearly 200 Mt N, while [Fowler et al. \(2013\)](#) put the total anthropogenic emissions at about 210 Mt N/year.

The mass of the fixed anthropogenic nitrogen is thus significantly larger than the total of the premodern mobilization of the nutrient's reactive forms, and this enlargement and acceleration of flows has had a number of environmental consequences. Above all, this reaction is due to relatively low recovery efficiency of nitrogenous fertilizers by rice, wheat, and corn, the three cereals that receive most of the applied nitrogen (commonly more than 100 kg N/ha every year). Global mean for the three crops is on the

order of 50% recovered by harvested grain ([Smil 2001](#); [Ladha et al. 2005](#)). A global assessment showed a distinct decrease of nitrogen utilization efficiency between 1961 and 1980 (from 68% to 45%), followed by a stabilization at around 47% ([Lassaletta et al. 2014](#)).

Excessive application of nitrogenous fertilizers has been responsible for acidification of soils, particularly in China, where urea has been used in record amounts in order to sustain high yields of rice. Two nationwide surveys, one from the 1980s and the other one from the 2000s, showed average pH decline of well over 0.5 (that is a tripling of the mean acidity), with some soils having acidic pH as low as 5–5.5 ([Guo et al. 2010](#)). Neutralizing these changes would require large applications of CaCO_3 .

In addition to acidifying soils, reactive nitrogen compounds enter the atmosphere through volatilization and denitrification and contaminate waters by leaching (as soluble nitrates) and by being carried away from fields by runoff and erosion. The three most important consequences of these losses are emissions of a potent greenhouse gas, atmospheric deposition of nitrates and ammonia, and eutrophication of ecosystems ([Fowler et al. 2013](#)). Nitrous oxide contributes to anthropogenic global warming. Dry and wet deposition of nitrates (produced by atmospheric reactions from NO_x emissions) contributes to acidification of soils and waters. And leaching and runoff of reactive nitrogen enrich waters and the resulting eutrophication produces algal growth whose eventual decay creates hypoxic and anoxic dead zones in coastal ocean waters ([Diaz and Rosenberg 2008](#)).

Intensified fertilization has been a major factor in the creation and enlargement of dead zones around the world. Nitrogen discharges to coastal waters rose by more than 40% during the last three decades of the 20th century, with some 75% originating in fertilizer ([Bouwman et al. 2005](#)). More than 500 coastal water areas have oxygen concentrations below 1 mg/L (the level defining hypoxia), while fewer than 10% of them were known to be depleted in oxygen by 1950 ([Breitburg et al. 2018](#)). The largest ones have formed in the northern Gulf of Mexico; in Europe in the North, Baltic, and Black Seas; in Asia in the East China Sea; and off South Korea and Kyushu Island ([NASA 2008](#)). In addition, the open ocean has now lost about 2% of its oxygen since the late 1960s and open water with minimum oxygen levels has expanded to cover an area whose size is comparable to the European Union.

Improving this situation will not be easy: as already explained, global population is now existentially dependent on nitrogen fertilizers: they now secure the prevailing diets for about 45% of the world's population, or more than three billion people—while in China and India the shares are more than 60% ([Ma et al. 2010](#); Pathak et al. 2010). There are only two effective options to lower nitrogen applications. Better agronomic management would cut nitrogen's field losses but it requires combined, well-executed, and costly steps by relying on split fertilizer applications, balanced use of nutrients, precision farming, rotations with leguminous crops, and the use of expensive slow-release fertilizer compounds.

A second option is that affluent countries could achieve greater and faster savings by cutting down on their average meat consumption. Given the combination of the prevailing low rates of nitrogen recovery by crops, of their large share used for animal feeding, and of low feed-to-meat conversion efficiencies, the overall nitrogen efficiency of the global food system is no more than 15% ([Smil 2013b](#)), with the US rate at only about 12% ([Howarth et al. 2002](#)) and the Chinese rate at just 9% ([Ma et al. 2010](#)). But any substantial cuts in meat production would disrupt farming system (be it in the United States or China), and even if such steps were relatively effective much more nitrogen will be needed in Africa, where the use of synthetic fertilizers is a small fraction of the Asian mean (and an order of magnitude below desirable levels) and where most of the world's population growth will take place during the remainder of the 21st century.

Phosphorus does not cycle rapidly, because its natural mobilization (part of the geotectonic denudation-uplift cycle) is very slow, solubility of phosphates is very low, and their rapid transformation to insoluble forms puts it beyond the reach of plants, making it the key growth-limiting nutrient, especially in aquatic ecosystems ([Redfield 1934](#); [Smil 2000b](#)). Human activities accelerated the element's natural flows due to increased soil erosion and runoff from arable land, by producing, recycling, and releasing larger masses of organic wastes (often discharged without any treatment into streams, lakes, and coastal waters) and, most importantly, by applying inorganic fertilizers. By the beginning of the 21st century these activities mobilized annually at least five times as much phosphorus as did the premodern global flows.

Inorganic fertilizer applications began in the 1840s with calcium phosphate. Thanks to its large Florida deposits, the United States became

the largest producer of phosphate rocks during the 1880s, and only in 2005 was it surpassed by China, with Morocco and Russia being the other leading producers (USGS 2018). Global production of phosphate rock is now close to 250 Mt and the annual supply of phosphatic fertilizers is just over 50 Mt when expressed (as is common in fertilizer statistics) in equivalents of P_2O_5 and about 22 Mt in terms of elementary P (FAO 2017b). Global food production is now critically dependent on phosphates, which now account for 60% of all phosphorus inputs in cropping, with recycling of organic matter being a distant second source. Again, the greatest deficits of the nutrient are in Africa.

Uptake efficiencies by plants are on the order of 50% and, as in the case of nitrogen leaching, phosphorus losses are a major contributing cause of eutrophication. According to Redfield's ratio (Redfield 1934), an atom of P supports 16 times as much aquatic photosynthesis as an atom of N, and additions of phosphorus often produce rapid (and naturally self-limiting) algal blooms and exacerbate the subsequent formation of dead zones in the ocean. As with nitrogen losses, the most effective way to reduce the unwanted presence of phosphorus in waters of affluent countries is to reduce meat consumption and to follow the best agronomic practices.

Unlike the highly mobile reactive nitrogen, dissolved superphosphates react with alkaline elements, aluminum, and iron present in soils to produce fairly insoluble compounds. This process of immobilization (fixation) of phosphorus has been known since 1950 and it led to concerns about eventual exhaustion of phosphate reserves because of the element's retention in insoluble forms in agricultural soils. In reality, sandy soils and soils with nearly neutral pH have low retention, and once the fixation capacity of more receptive soils has been saturated, subsequent applications are needed just to replenish the nutrient taken up by plants and lost by leaching. Moreover, phosphorus from urban wastes could be removed by physicochemical processes that include precipitation, sorption, and ion exchange mechanisms, and then recycled (Bunce et al. 2018).

Global Changes

Our planet's most distinguishing feature is the presence of life and hence the most fundamental appraisal should look at the changes of the total mass

and the proportions of life on the Earth that human actions have caused. The other two approaches of global impacts take into account changes of many variables: the first one attempts to quantify the overall ecological footprint of humanity and of appropriate carrying capacity; the second one tries to define a safe operating space for humanity (Rockström et al. 2009). The chapter's remainder will deal with the global climate change, the most consequential anthropogenic transformation.

Appraising the planetary impacts

Small populations of preagricultural societies and their simple tools limited the overall human impact on biota. The only notable (already noted) exception may have been the contribution of Neolithic hunters to the extinction of Eurasian and North American megafauna. The pace of change accelerated with the diffusion of cropping but quantification of the subsequent decline of plant cover and of the concurrent reduction of mammalian zoomass can be done only in approximate manner. The same is true about the long-term increase of human biomass (anthropomass) because there is no good agreement about the total number of humans living back in 10,000 or 5000 BCE.

On the assumption that 10 million people were alive in the year 5000 BCE, their anthropomass would have been no more than 0.5 Mt. By 1900 the total anthropomass was about 75 Mt in the year 2000 it was 300 Mt. These numbers imply a 600-fold increase in seven millennia and a quadrupling during the last century. Reconstructions of the past biomass of invertebrate and vertebrate species would be just best guesses, but the margin of error for such totals gets smaller when only the totals of wild terrestrial mammalian zoomass are being quantified.

My best reconstruction added up to just 40 Mt of live weight in 1900 and to 25 Mt in the year 2000, a loss of 35%–40%; for comparison Bar-On et al. (2018) put the wild mammalian zoomass at about 14 Mt. Consequently, the global anthropomass had surpassed the terrestrial zoomass sometime around the mid-19th century and now it is an order of magnitude larger. But what I found most surprising is that in many places the anthropomass is now surpassing not only the zoomass of wild vertebrates but even the total biomass of soil invertebrates. In terms of live weight, chimpanzee zoomass prorates usually to less than 0.5 kg/ha. Intensive traditional agricultures

could support more than five people, or at least 200 kg/ha, and China's current ratio is about 15 people, or at least 650 kg/ha.

The last rate is equivalent to about 225 kg of dry biomass—while the total dry matter zoomass of soil fauna (mainly earthworms, myriopods, nematodes, mites, and springtails) in temperate cropland is typically less than 100 kg/ha ([Coleman and Crossley 1996](#)). This means that the normal trophic order—microbial biomass > invertebrate biomass > vertebrate zoomass > anthropomass—that had prevailed in agroecosystems for millennia has been reversed, thanks to large-scale energy and nutrient subsidies, and that in many regions high crop yields now support anthropomass larger than the mass of all soil invertebrates. Few comparisons can equal this demonstration of human ascendance.

But humans do not dominate the world's mammalian biomass; their domesticated animals do. In 1900 the total count of large domestic animals (cattle, water buffaloes, and pigs) reached about 1.6 billion, in the year 2000 it had surpassed 4.3 billion. My calculations of their live weight (using appropriate body-mass averages) indicate no less than 170 Mt of domesticated zoomass in 1900 and at least 600 Mt in the year 2000 ([Smil 2013a](#)). This finding implies that in 1900 the mass of domesticated animals was more than four times as large as that of wild mammals and that this difference widened to be about 25-fold in the year 2000. Even a major underestimate of surviving wild animals could not change the conclusion that as far as mammals go, this is now the planet dominated by cattle, pigs, and people, not by free-roaming herbivores and carnivores. My best estimate is that even the mass of the world's largest terrestrial mammals, African elephants, is now less than 0.5% of the global zoomass of cattle.

Continental vegetation receded during the last Ice Age, and its Holocene gain that followed the greatest extent of glaciation had roughly tripled the total area of tropical rainforest while the area of cool temperature forests expanded more than 30-fold ([Adams and Faure 1998](#)). Standing stock of terrestrial phytomass could have surpassed 1,000 Gt C 7,000 years ago (after the glaciers had completely receded) and deforestation and cropland expansion had reduced that total to between 750–800 Gt C by the beginning of the 19th century. Losses during the past two centuries were no less than 150–200 Gt C, leaving the early-21st-century terrestrial stocks at no more than 650 Gt C and perhaps as low as 600 Gt C. These approximations imply

35%–40% reduction of the Earth's phytomass attributable to humans since the beginning of the agricultural era.

Another measure of this impact was to find what share of the biosphere's net primary production (NPP) is now appropriated by humans. Unfortunately, there is no universally valid definition of appropriation (should it include only actual removals of harvested phytomass or all indirect impacts?) and NPP is a questionable choice of a denominator because it is a theoretical construct, not a variable that can be actually measured and monitored in the real world ([Smil 2013a](#)). NPP is the total (gross) plant photosynthetic productivity reduced by plant respiration, and the resulting phytomass is available to be consumed by heterotrophs ranging from bacteria and fungi to insects and rodents. They consume variable (and often large, as in the case of locusts) shares of available phytomass, and what remains after this heterotrophic respiration is available for human harvests. But even that total is not the same as actual agricultural or forest productivity (crop and timber yields), because parts of plants remain unharvested (roots, stumps).

But NPP is certainly the broadest concept of photosynthetic output, and its global values used by studies of human appropriation have differed by as much as 40%, with the extremes at 57 Gt C/year ([Imhoff et al. 2004](#)) and about 80 Gt C ([Wright 1990](#)). The first assessment of planet-wide appropriation of biomass offered an unhelpfully wide range (3%–39%) but the paper became incorrectly cited as a proof that humans already harvest some 40% of all NPP ([Vitousek et al. 1986](#)). Subsequent evaluation of NPP appropriated or co-opted by humans ranged from 24 to 55% ([Wright 1990](#); [Rojstaczer et al. 2001](#); [Imhoff et al. 2004](#); [Haberl et al. 2007](#)). My comprehensive evaluation concluded that during the first decade of the 21st century all annual harvests (and direct destruction) of terrestrial plant mass totaled about 20 Gt of dry plant matter, an equivalent of about 10 Gt C ([Smil 2013a](#)).

When we assume the most widely accepted rate of NPP (60 Gt C/year), that removal corresponded to nearly 17% of its total, or to only about 13% when we assume a higher NPP rate of 75 Gt C/year. These shares are (not yet) alarmingly high but a more important conclusion is that NPP-based “appropriation” ratio has too many problems (above all its omission of many qualitative changes) to be recommended as a preferred measure of the human impact on the biosphere. Whatever today's actual share may be, it

will continue to rise: otherwise it would be impossible to improve the lives of more than five billion people now living in low-income countries and an additional two billion who will be, most likely, added by the end of the 21st century.

The two related approaches that assess the overall global burden are the quantification of ecological footprints and appropriate carrying capacity (Rees 1992), and the definition of a safe operating space for humanity (Rockström et al. 2009). The first choice is particularly questionable because carrying capacity is not fixed (it changes with human advances and its limits are not necessarily those we can define now) and because it aggregates different attributes, dimensions, and scales into a single index. The index is now published annually for the Earth and for some 200 countries by the GFN (Global Footprint Network) (2018) and it seriously misrepresents many complex realities (Giampietro and Saltelli 2014). According to this metric, we are now using 1.7 Earths. Spurious accuracy of this accounting is perhaps best illustrated by marking, to a day, the annual time of the planetary overshoot. In 2018 the date “when we (all of humanity) have used more from nature than our planet can renew in the entire year” fell on August 1 (GFN 2018).

Critique of the measure aside, there is no doubt that too many countries have been taxing their environment beyond levels compatible with the survival on a civilizational time scale: that is, on the order of 10^3 years. The notion of the safe operating space for humanity links this survival to the planet's biophysical subsystems or processes, many of which respond to interferences in nonlinear ways. Rockström et al. (2009) identified nine of these processes and set their safe boundaries well below the biophysical thresholds in order to acknowledge some inherent uncertainties regarding their placement and to act as warnings by allowing time to react. The identified planetary thresholds that should not be crossed in order to prevent intolerable environmental change were climate change; rate of biodiversity loss (terrestrial and marine); interference with the nitrogen and phosphorus cycles; stratospheric ozone depletion; ocean acidification; global freshwater use; changes in land use; chemical pollution; and atmospheric aerosol loading.

The first assessment concluded that by 2009 we have already passed their boundaries, and that the safe boundaries of global freshwater use, change in land use, ocean acidification, and interference in the global phosphorus

cycle were fast approaching. A revised assessment extended the time span to 2010 and adjusted some definitions. The trajectory of the Anthropocene was called “The Great Acceleration” and the analysis confirmed that safe boundaries were surpassed for several key variables ([Steffen et al. 2015a](#)). The most worrisome increases were for CO₂ (the safe boundary at 350 ppm CO₂), for change in biosphere integrity (with the tolerable range defined as 10–199 extinctions per million species per year), for ocean acidification (no more than 80% of the preindustrial aragonite saturation state of mean surface ocean), and for biogeochemical flows (especially for nitrogen fixation at 62–82 Mt N/year).

Climate change

No other global environmental change is as consequential as the increase of atmospheric greenhouse gas concentrations in general and of anthropogenic CO₂ in particular. The reason is simple: the resulting climate change will affect all parts of the biosphere as well as all human activities. Emissions of CO₂ and their consequences have received a disproportionate attention ever since global warming became the leading environmental concern, first (during the late 1980s) in affluent nations, soon afterwards globally (the first UN Climate Convention was in 1992). But there is nothing new about our understanding of the greenhouse gas effect, about its necessity for life on the Earth, and about its link with climate.

During the late 1820s Joseph Fourier, a French mathematician, described the atmosphere acting like a greenhouse glass, letting the light through but blocking the escape of invisible reradiated rays. By 1861 John Tyndall identified water vapor as the dominant absorber of the outgoing radiation ([Tyndall 1861](#)), and in 1896 Svante Arrhenius published the first calculations of global temperature rise caused by an eventual doubling of preindustrial atmospheric CO₂: he predicted an average annual increase of 4.95°C in the tropics and just over 6°C in the Arctic, very much within the range of the latest computer models of global climate ([Arrhenius 1896](#)). The stakes involved in further CO₂ emissions have been known for more than a century—but, at the same time, the existence of life on Earth depends on the presence of greenhouse gases. In their absence, the Earth’s surface would be frozen at –18.1°C; thanks to their presence, it averages 15°C.

Water vapor accounts for nearly two-thirds of the overall effect; CO₂ for nearly a quarter; and CH₄, N₂O, and O₃ for most of the rest. CO₂ resides in the atmosphere for hundreds of years, and as its concentrations rise they change the biosphere radiation balance: since the middle of the 19th century radiative forcing attributable to CO₂ has been about 2 W/m², and the total is about 3 W/m² after adding the effect of other greenhouse gases (Butler and Montzka 2019).

During the past millennium the concentrations of CO₂ have been remarkably stable, ranging from the low of 275 ppm in the early 17th century to the high of nearly 285 ppm during the late 12th century (CO₂-Earth 2019; Figure 6.1). In contrast, the recent gains have been extraordinarily rapid, reaching 350 ppm in 1998, 400 ppm in 2015, and surpassing 414 ppm by July 2020 (NOAA 2020).

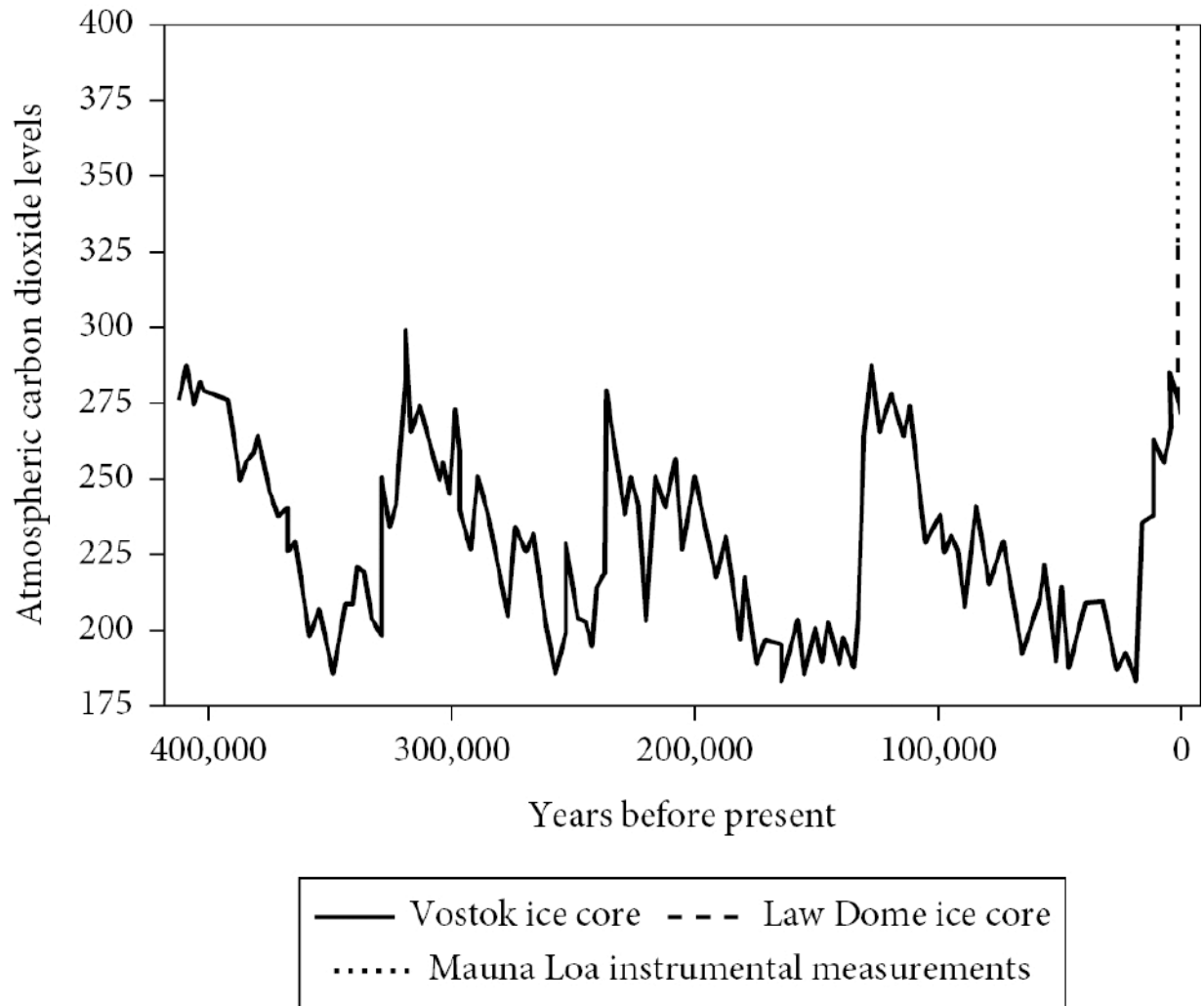


Figure 6.1 Growth of atmospheric CO₂ concentrations: the last 400,000 years from ice cores and since 1959 from Mauna Loa measurements. Data from CO₂-Earth (2019).

But the other greenhouse gases are, mole for mole, significantly higher absorbers of the outgoing infrared radiation, but they do not reside in the atmosphere as long as carbon dioxide. In order to account for these differences, the warming impact of other greenhouse gases is expressed in terms of CO₂ equivalent (CO₂e) on the basis of the global warming potential (GWP), a measure that quantifies equivalent effects of various gases over a 100-year period. GWP for the simplest chlorofluorocarbon formerly used as a common refrigerant (CCl₃F) is 3,800 CO₂, for N₂O it is 310, and for methane it is 21 (IPCC 2007). On a 20-year basis methane's warming potential is about 72, but on a 500-year span it shrinks to less than

8. CO₂ emissions now account for about 75% of the total GWP, with nearly all of the rest originating from methane (about 16%) and nitrous oxide (IPCC 2014).

Major uncertainties remain despite the enormous research interest in all aspects of the global warming, but the emission trends are clear: after four generations of steady rise, all of the major sources of fossil CO₂ recorded significant increases since 1992, the year of the first global convention on climate change (UN 1992). During the subsequent 25 years emissions from coal rose by 70%, from crude oil by 37%, and from natural gas by 83%, with the aggregate of 54% for all fossil fuels. And production of some key materials and processes dependent on fossil fuels either for feedstocks or fuels had even higher gains: 60% for ammonia, 90% for pig iron, and 230% for cement, while the annual registration of motor vehicles had nearly doubled and airplane deliveries increased by almost 150%!

Periodical summaries of our understanding of the global warming are prepared by the Intergovernmental Panel on Climate Change (IPCC 2014). Those unwilling to endure the immersion in thousands of pages of specialized reports should look at least at the summary of the latest report on the global warming of 1.5°C (IPCC 2018). So far human activities have raised the average global temperature by about 1°C and, at the current rate of emitting greenhouse gases, the increase of 1.5°C is expected between 2030 and 2052.

Consequences and trends

Future temperature increases will not be evenly distributed (IPCC 2014). While the global mean is now about 1°C above the preindustrial average, annual Arctic temperature anomalies are now nearly 3°C higher, and the associated environmental changes are expected to intensify. They include decreased sea ice cover in summer, diminished snow cover in winter, reduced volume of glaciers, widespread degradation of permafrost, increased river discharge, higher lake water temperatures, increased shrub cover in tundra, and advances of the Arctic tree line, both in latitude and altitude, that will change breeding areas and population sizes of subarctic animals (IPCC 2014).

Higher summer extremes are of the greatest concern in large cities where air conditioning remains rare (as it does in Europe) and in the Middle East,

the region whose social and economic conditions have been already fractured by recurrent violence and inequalities. Some regions have already seen increased frequency of heavy precipitation, particularly in winter, and such events could be more frequent and more intense over the mid-latitude regions (IPCC 2014).

The combination of higher CO₂ levels and higher average temperatures should enhance plant productivity. Even at more than 400 ppm today's CO₂ concentration is far below the level that would saturate the photosynthesis of C₃ plants: that is, most forest trees and all major crop species except corn and sugar cane. Further productivity gains should arise from higher water-use efficiency of C₃ plants (they could produce more even in areas with somewhat lower precipitation). These expectations were confirmed by extended field studies of crops and trees exposed to higher levels of CO₂ (Peters et al. 2018). Higher annual productivity has been observed for most of the United States during the latter half of the 20th -century as well as for China's forests (Nemani et al. 2002; Tao et al. 2007), and Nemani et al. (2003) already confirmed the effect on the global scale: between 1982 and 1999 worldwide NPP increased by about 6%.

And while increased temperatures would lengthen average growing seasons in higher latitudes, terrestrial ecosystems would remain highly sensitive to temperature changes (Nolan et al. 2018). Moreover, higher productivity may be limited by nutrient shortages and by minimal response of mature trees. Confident conclusions about the net response of plants in a warmer world with higher CO₂ concentrations remain elusive. A large share of rising CO₂ emissions has been absorbed by ocean and this process is gradually acidifying sea water, a change that will impact all marine biota and especially all organisms sequestering calcium. Ocean acidification will not make seawater acid (that is pH<7.0) but it has already made it less alkaline: during the past two centuries the progressing surface water pH was lowered from 8.2 to 8.1, and that is (on a logarithmic scale) nearly a 30% decline.

Seawater is supersaturated with CaCO₃ minerals (calcite and aragonite) that are used by calcifying organisms (mollusks, corals, and phytoplanktonic foraminifers and coccolithophores) to build their shells and skeletons. As many parts of the ocean will become undersaturated with calcium carbonate minerals, some calcifiers will find it increasingly

difficult to build and maintain their mineral parts. Higher water temperatures also lead to coral bleaching as the invertebrates expel the algae (zooxanthellae) that live in their tissues and the invertebrates turn white. These episodes may be survivable but usually they entail significant coral mortality, and as the intervals between successive episodes become shorter there may not be enough time for full recovery. [Hughes et al. \(2018\)](#) analyzed bleaching records at 100 reef locations around the world between 1980 and 2016 and found that the median return time between pairs of severe bleaching events has been steadily declining.

We have already seen northward shifts of some plant and animal ranges, and assessment of growing degree days showed that while in 2017 only 32% of the boreal region had conditions suitable for the cultivation of small cereals, by 2099 about 76% of that region might be suitable for their cultivation, with the leading edge shifting northward up to 1,200 km ([King et al. 2018](#)). Recent large-scale fires in Australia, North America, and Europe focused public attention on yet another changing phenomenon. At the same time, the increased frequency of forest fires is also linked to decades of fire suppression and to human settlements encroaching on forests.

The scale of the challenge and its inescapably interrelated nature will make dealing with these environmental changes extraordinarily difficult. Past transformations of agricultural, energetic, and economic foundations have been one thing, even in the case of populous nations; displacing 10 billion metric tons of fossil carbon in a matter of decades while assuring an adequate food and energy supply for some 10 billion people and sustaining the global economy producing every year in excess of \$100 trillion is quite another challenge.

Outcomes and Outlooks

Change is the essence of evolution but the rate of change varies greatly and it is revealing to put the outcomes of grand transitions into wider perspectives. I will do that by focusing on their rates and scales. Such comparisons and summaries offer convincing evidence about the extent of the transitions and about their consequences for human well-being. And yet these outcomes have not been fully appreciated, because the undoubted accomplishments have not received the same attention as the saturation coverage of failures, setbacks, and supposedly looming catastrophes provided by mass media.

This bias has been frequently carried forward. Since the 1960s, predictions of runaway population growth, food crises and famines, environmental degradation, imminent energy shortages, and ensuing economic collapse have received widespread coverage—yet none of those apocalyptic visions that have been offered during the past half a century has come to pass. Getting the past and current facts straight is important, and seeing the recurrent catastrophic claims with plenty of skepticism is highly advisable. At the same time, getting carried away and assuming that the future will be nothing but a superior version of the past accomplishments is highly imprudent. Accomplishments of the modern civilization inspire hope and instill confidence in our problem-solving abilities—but the recitals of advances should not ignore many fundamental limits and undesirable trends whose combined effects will make future grand transitions extraordinarily difficult.

What We Have Accomplished

The Sun belongs to what astronomers call main sequence stars that fuse hydrogen atoms to produce helium at their cores and radiate enormous

quanta (4^{27} W) of energy; this sequence began about 4.6 billion years ago and it has another 4.5–5.5 billion years to go before the star will enter its red-giant phase (expanding beyond the orbit of Venus) that will precede its final collapse to form a white dwarf. The Earth itself is 4.5 billion years old, and for more than half of that time it has been under conditions not greatly dissimilar to our current state: that is, with continents risen above the ocean and with an oxygenated atmosphere ([Smil 2002](#)).

Compared to these cosmic and geologic time scales (10^9 years) the changes that have taken place since the emergence of sapient humans appear to be nearly instant. Their scale is best illustrated by tracing the orders of magnitude, but as with all large multiples, our comprehension soon reaches its experiential limits. An order of magnitude is, of course, a tenfold difference, a gain that is readily imaginable when going from 1 to 10 or from 10 to 100, but impossible to visualize when going from 10 to 100 million (10^7 to 10^8).

Rates of change

There are continuing uncertainties about the first appearance of modern humans, but the divergence is now put as far back as 260,000–350,000 (10^5) years ago ([Schlebusch et al. 2017](#)). By 10,000 BCE there were a few million people (10^6) on all habitable continents, all of them foragers. By 4000 BCE the total approached 10 million (10^7), with increasing numbers of people living in settled agricultural societies, a transition that in some regions took only a few thousands of years to accomplish. The next combination of quantitative and qualitative transitions was even faster and also more impressive: around 500 BCE (when Pythagoras died and two generations after the Boeotian League was established) the global population reached 100 million people (10^8), with most of them living in complex sedentary societies governed from cities and displaying remarkable structures and works of art

After a millennium of further gradual advances—including the rise and expansion of three major and long-lasting empires, the Roman Empire centered in the Mediterranean (originally as a republic in 509 BCE, an empire from 27 BCE until 466 CE), the Parthian Empire in the Middle East (243 BCE to 224 CE), and the Han dynasty in China (206 BCE to 220 CE)—

followed a period of relative population, technical, and economic stagnation marked by very low growth rates and fitful advances mixed with setbacks. This bleak situation began to change in the 16th century with the onset of the early modern era as European societies began to move past the formerly technically more advanced China through a process that combined imperial conquests with scientific breakthroughs, and that evolution set the foundations for modern civilization.

Global population took more than two millennia (about 2,300 years) to make an order of magnitude gain from 100 million to 1 billion (10^9) early in the 19th century. And although all reconstructions of ancient, medieval, and early modern economic products are highly questionable, it seems likely that the world's economic output needed a comparable period of time to grow by an order of magnitude, not a surprising outcome, given that its annual growth rates were for centuries below 0.01% and later, at best, merely 0.1–0.2%, and were repeatedly interrupted by generations of no gains.

Then a concatenation of great accelerations set in, as all fundamental measures of social and economic development, quality of life, and organizational complexity began to grow, often in unison and at unprecedented rates, resulting in shifts and outcomes that have, with a few generations, created modern societies. Global population continued its super-exponential growth until the 1960s and by that time it had quadrupled in just eight generations; the subsequent growth rate declined but the growing base still resulted in the sextupling of global population in the 200 years since 1800. It now looks very likely that the next order of magnitude (10 billion people, 10^{10}) will be reached before 2100, less than 300 years after surpassing 10^9 .

Perhaps the most remarkable characteristic of the modern era is that the growth rates of food and energy supply and of the total economic output, the fundamentals of human existence, have been surpassing the growth rate of global population (1.3% during the 20th century) by significant margins, resulting in substantial per capita gains. Food production was elevated from the conditions of chronic insufficiency to the state of excess in high-income countries (with waste up to 40% of all produced food) and to basic or comfortable sufficiency even in the world's most populous nations, including China, India, Indonesia, and Brazil. China's average per capita

food supply is now higher than in Japan; the Brazilian mean is nearly the same as the Australian average ([FAO 2019](#)).

My reconstruction of the 20th century's crop harvests shows that their total output (expressed in energy terms and including their residues) increased sevenfold and hence its average annual growth rate of 1.9% was 50% above the population's annual expansion. This increase has led to a steady decline of the global share of malnourished and undernourished population and it allowed substantial increases in the consumption of animal foods: for the first time in history significant shares of crop harvests could be diverted from food to animal feed, and the global meat production, growing at 1.9% a year, had quintupled during the 20th century.

Primary energy supply has undergone the transition from the world dominated by biomass fuels and animate energies to a new complex system relying overwhelmingly on fossil fuels (supplemented by hydro- and nuclear electricity) and inanimate prime movers. During the 20th century the supply of these new energies grew at an average annual rate of about 2.8% (more than twice as fast as the global population)—but a proper comparison must take into account the intervening gains in energy conversion efficiencies: doing so puts the average annual growth of useful commercial energy at about 3.7%, nearly three times as high as the aggregate population growth rate.

Totals of the global economic output have all the problems of their constituent national measures, and their long-run estimates are always only more or less defensible approximations that require further conversions to a common currency (usually the US\$) and adjustments in constant monies in order to make international and secular comparisons. For all of these reasons it is better to cite just the indicative growth rates rather than actual monetary values. [DeLong's \(1998\)](#) series shows average annual growth of 2.7% for the two centuries between 1800 and the year 2000 and [Maddison's \(2007\)](#) series implies annual growth of 2.2% between 1820 and 2003, both far ahead of the average population growth and hence resulting in appreciable per capita gains.

Scales of change

In order to summarize these advances I have assembled data on annual worldwide production of the key enabling variables during the 20th

century: that is, for energy (the three kinds of fossil fuels and total electricity generation), the two leading fertilizers (N and P, delivered as synthetic ammonia and superphosphates made by the acidification of phosphate rock) and four dominant materials (cement, steel, plastics, and aluminum) (Figure 7.1). One of the most notable features of this comparison is its novelty: it could be done for only two items during the 19th century because in 1800 only a relatively small amount of coal and a much smaller mass of steel were produced commercially, with the United Kingdom being the leader in both cases.

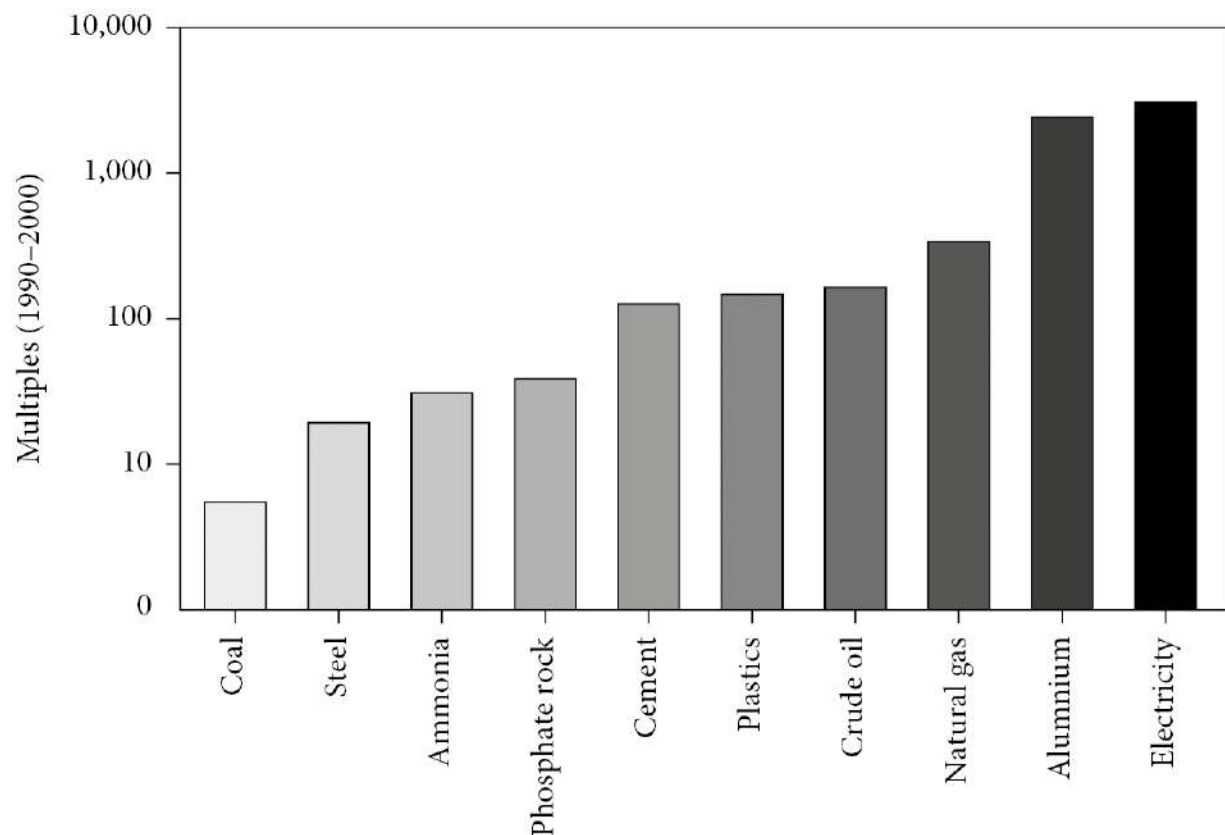


Figure 7.1 The 20th-century multiples for the production of major forms of energy and for the most important materials. The generation of electricity, smelting of aluminum, and fixation of nitrogen had seen the largest expansions; multiples for ammonia and plastics are for 1950–2000. Calculated from data in Smil (2001, 2014, 2016a, 2017b).

In contrast, by 1900 all but one of today’s key enabling inputs (synthetic ammonia, whose production began in 1913) became commercial, although the production of plastics began to grow significantly only with the introduction of Bakelite after 1910. As a result, we cannot calculate the

multiples for ammonia and plastics but the multiples for 1950–2000 are, respectively, about 30- and 120-fold. For other inputs (excluding coal and including steel and phosphate rock), gains during the 20th century were at least one order of magnitude, crude oil and natural gas extraction and cement production expanded by two orders of magnitude, and aluminum smelting and electricity generation rose by three orders of magnitude.

Consequences of these interrelated output multiples can be seen in accompanying quality-of-life gains, including increased longevity; extended spans of active life; higher levels of education, and income; a greater affordability of products that make life more comfortable, increased frequency of travel; and in the availability and cost of information and communication. Most of these gains have advanced concurrently and have benefited ever larger number of people. Obviously, neither life expectancy nor literacy in industrialized countries could have improved even by an order of magnitude during the 20th century, but typical Western gain for longevity was about twofold between 1800 and 2000, from about 40 to nearly 80 years. In 1900 the share of literate population was already high in Western Europe (about 80%) but the global mean was only 35% and the East Asian share reached only 30%; by the year 2000 the all-European mean was virtually 100%, the East Asian mean had approached 90% and the global mean close to 80% ([van Leeuwen and van Leeuwen-Li 2014](#)).

According to Maddison the average global gain of per capita GDP was an order of magnitude between 1820 and 2003, with national multiples ranging from 30 in Japan, nearly 25 in the United States, about 18 in Germany, and 12 in the United Kingdom, while [DeLong's \(1998\)](#) global GDP estimates imply a roughly 40-fold average rise since 1800 and almost exactly a tenfold gain during the 20th century. Among the major economies the largest multiple has been recorded by China. The country had essentially no growth of per capita GDP between 1800 and 1950 and the rate had only about doubled during the next quarter century (Mao Zedong died in 1976). The economic reforms began slowly in 1980 and by the year 2000 China's PPP-adjusted per capita GDP had grown 12-fold and the additional increase by 2019 was nearly tenfold, or almost a 120-fold gain since 1980. This extraordinary multiple has been due to a trifecta of being a late starter (and hence taking the advantage of the best available technical options), of receiving enormous amounts of direct foreign investment, and of becoming the world's largest export-oriented manufacturer.

Long-term multiples for overall mobility are not easy to construct. An aggregate measure would have to combine the succeeding waves of dominant modern transportation modes and capacity of widely used carriers and typical distances traveled—and the resulting aggregate would conceal the different reasons for moving around. For example, large passenger-kilometer totals can be obtained by mass-scale short-distance commuting to work as well as by frequent long-distance intercity flying. US transportation statistics make it possible to reconstruct the aggregates of pkms in 1900 and the year 2000 (USBC 1975; BTS 2019). In the first instance the total is just for railway traffic (only about 2,500 cars were made in the United States in that year, and the first US commercial flight took place in 1914) and a century later it is the combination of passenger cars, scheduled flights, and railway transport: the multiple for the 20th century is on the order of 200, with automotive pkms accounting for about 85% of the total in the year 2000.

In affluent countries the gains in personal mobility have been thus of a similar order of magnitude as the gains for several energy and material inputs, and all of these appear insignificant when compared to long-term gains in information and communication. Their indicators were first multiplied during the 19th century by advances in rapid printing, photography, and audio recordings and by the production of inexpensive paper made from wood pulp. The first half of the 20th century brought even more affordable printing, recordings, and image reproduction as well as movies and television. Subsequent expansion of digital information has dwarfed all previous gains. By 2016 the worldwide information storage surpassed 16 ZB, 11 orders of magnitude (320 billion times) higher than the total reached 2000 year ago ([Seagate 2017](#)).

Perhaps the best metric for quantifying the gains in communication is the cost of an international phone call. Again, there can be no comparison for the entire 20th century: intercity phone service was available in parts of the United States since the early 1880s, but the first transcontinental call (from San Francisco to New York) was made only in January 1915 and the first trans-Atlantic call (from London to New York) only in March 1926. Starting with the typical charge for an international call in 1930, the relative cost fell by 90% in 1972, to less than 1% in 1993 and to just 0.1% in the year 2000 (OECD 2013), a 1,000-fold decline in 70 years. And during the first 15 years of the 21st century the cost fell by another order of magnitude

(Figure 7.2). And in the era of e-mail, Skype, Facebook Messenger, WhatsApp, WeChat, Telegram, Viber, or Google Hangout, when an individual can reach simultaneously, and virtually cost-free, large numbers of people anywhere in the world, waiting for an operator to connect an expensive intercontinental call on an indistinct line with a distinct delay is a distant memory.

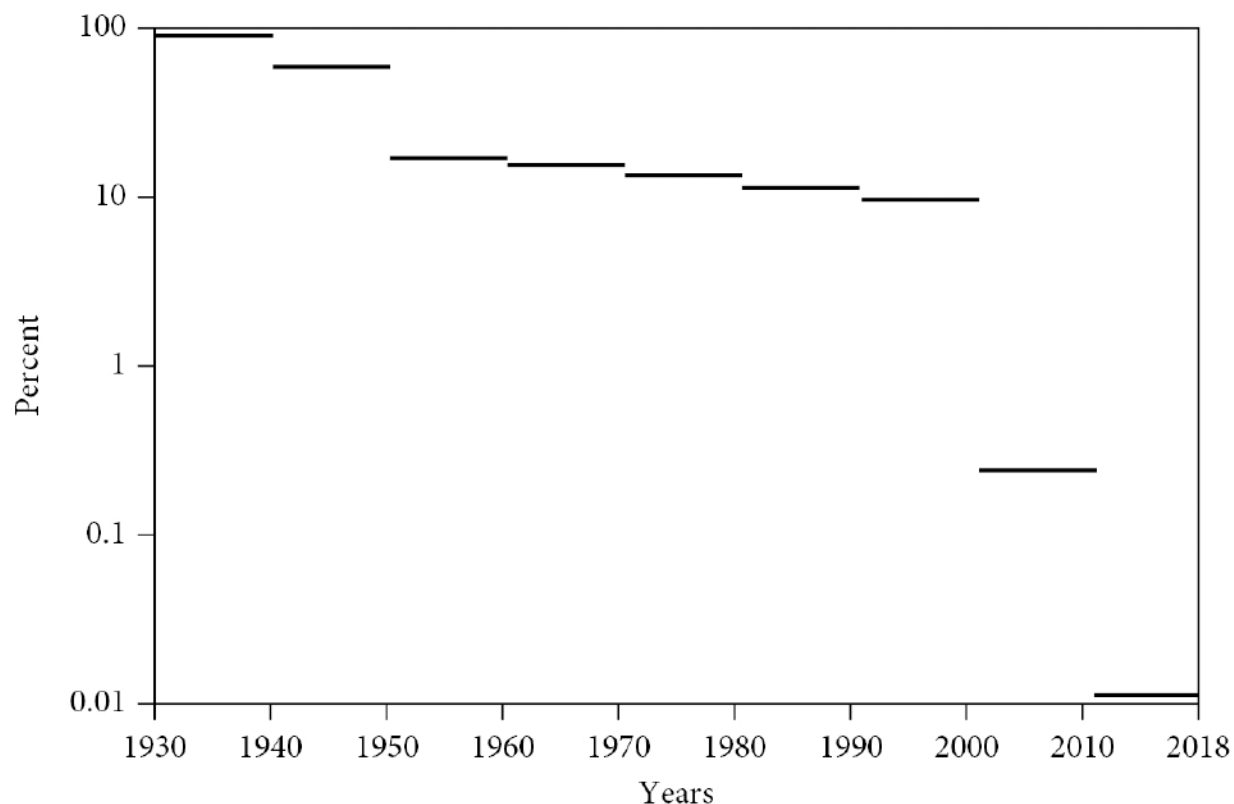


Figure 7.2 Declining cost of international telephone calls. Compared to 1930 a short trans-Atlantic call is now four orders of magnitude ($1/10,000$) cheaper. Plotted from data in OECD (2013) and [Rodrigue \(2017\)](#).

Arthur C. Clarke's often cited (and highly perceptive) Third Law states that any sufficiently advanced technology is indistinguishable from magic ([Clarke 1962](#)). The claim could be easily repurposed for describing the quality-of-life gains that have resulted from the two centuries, and in many cases from just one century or its fraction, of grand transitions. Typical longevities, levels of income, amenities of quotidian existence, incessant flows of energies, variety of food, ease and affordability of travel, surfeit of virtually cost-free information—all of these gains have been truly magical

for two reasons. First, most of today's indispensable enabling inputs (from ammonia synthesis to electricity generation) and resulting benefits (from antibiotics to refrigeration) did not even exist two centuries ago. Second, life expectancy aside, the gains for the 20th century have not entailed mere doubling or tripling of the early performance: their multiples have been typically at least one, more often two or three orders of magnitude, improvements whose extent cannot be easily conceptualized and that, in retrospect, appear truly magical.

What to expect?

This book's very *raison d'être* is to explain the genesis and follow the trajectories of these undeniable improvements by resorting to (some may feel) excessive frequency of numbers. I believe this approach is necessary in order to document these grand transitions in their complexity, by showing the remarkable gains as well as many worrisome consequences, and to convey the epochal accomplishments of these concatenated processes and their inherent complications. For those reasons I reject using either the failures and losses or the gains and advances as the dominant templates in assessing the future transitions—but this stance is in contrast with the two dominant visions of darkly catastrophic and ever-brighter futures.

The first set of expectations has ancient apocalyptic pedigrees but its modern practitioners do not skimp on dramatic descriptions as they offer their tales of imminent collapse and mass suffering. The Roman Empire is a preferred template of collapse, a practice that ignores two important realities. First, the empire's eastern part (the capital was removed from Rome to Constantinople in the year 330) continued to prosper (even to expand) for hundreds of years and it had survived almost exactly for another millennium after the last Western ruler was deposed in 476. Second, the manifold legacy of the Western empire had never disappeared, and after 800 CE it was resurrected in a major way in the West, providing an important political and cultural scaffolding for another 1,000 years of European history—and exerting many lasting influences in today's European Union.

No catastrophist forecast concerning population growth and food production has been quoted more as the paragon of utterly failed

expectations than Paul Ehrlich's conclusion that "the battle to feed all of humanity is over. In the 1970s hundreds of millions of people will starve to death. . . ." ([Ehrlich 1968](#), xi). But Ehrlich was not alone in predicting imminent apocalypses; he had just captured the tenor of the times more dramatically than others had done.

Robert L. Heilbroner's bestselling inquiry into the human prospect had this to offer about the imminent future of food: "World food stocks are today at their lowest point since World War II, and there is a general alarm concerning the possibility of unprecedented famines. . . . Meanwhile, world fish harvests have levelled off, or actually declined. . . . Finally, there appears to be no chance of building fertilizer plants rapidly enough to forestall a desperate food shortage in the underdeveloped world" ([Heilbroner 1975](#), 153–154). These forecasts were absolute failures: the realities have shifted in the opposite direction as hundreds of millions of people moved from uncertain subsistence to a comfortable food supply.

The prevalence of undernourishment in low-income countries has declined from 35% in 1970 to about 12% by 2018. The average global infant mortality rate has been more than halved since 1970, while by 2018 the worldwide production of staples was 2.5 times the 1970 level and overall marine harvest (catch and aquaculture) was almost three times higher ([FAO 2019](#)). Heilbroner, a professor of economics, should have consulted somebody who had basic information about nitrogen fertilizer plants using the Haber-Bosch process. There was no technical or economic problem for building additional plants, China became the world's largest producer of ammonia in 1989 (surpassing the USSR), oversupply of nitrogen fertilizers led to a substantial price drop during the early 1990s, and by 2018 global ammonia output was more than three times the total in 1975 ([FAO 2019](#)).

Instead, [Heilbroner \(1975, 161\)](#) extolled China as the ideal form of a society that "offers the greatest promise for bringing about the profound and painful adaptations that the coming generations must make." Writing a year before Mao's death, ignoring the horrific record of China's ruling Communist party (the world's greatest man-made famine, purges, and exiles affecting millions) and echoing the era's widespread infatuation with the new China, he concluded that

[w]e can discern in Chinese society certain paradigmatic elements of the future—a careful control over industrialization, an economic policy calculated to restrain rather than to whet individual consumptive appetites, and, above all, an organizing religiosity expressed through the credos and observance of socialist “church.”

Four decades later the same party is still in absolute control, its operating modes have shifted from inflicting mass suffering to asserting mass electronic control (the social credit system), and its post-Maoist policies have resulted in the world’s most rapid and most extensive industrialization and in an unprecedented quest for (legal and illegal) material consumption, including the world’s largest market for ostentatious luxuries and the world’s largest number of billionaires. China trying to out-American America is hardly a paradigm of profound and painful adaptations—and few examples offer such an embarrassing contrast between wishful thinking of some Western intellectuals and (not so surprising: Deng Xiaoping realized that in order to prevent new famines the country had to modernize) very different realities of China playing economic catch-up. Such recitals of failed catastrophic forecasts and profoundly misread realities could fill a book; their authors walk on well-trodden grounds.

This long tradition of catastrophic interpretations and predictions has been rejuvenated by recurrent claims of running out of resources in general and of crude oil in particular, by economic downturns, by terrorist actions, and by ever more worrisome claims about the impact of global warming. Those reasons are why Paul Ehrlich, writing 45 years after his failed famine forecast, concluded that because of growing environmental degradation “now, for the first time, a global collapse appears likely” ([Ehrlich and Ehrlich 2013](#), 1). And Ehrlich is far from alone. [Wallace-Wells \(2019\)](#) assures us that because of global warming all “is worse, much worse, than you think,” and the British Institute for Public Policy Research concludes that we have entered the age of environmental breakdown: natural systems are undergoing destabilization at an unprecedented scale and speed that create a new domain of risk and impact societies on levels ranging from local to global, pushing them to the limit (Laybourn-Langton et al. 2019).

Perhaps the most worrisome recent appraisal of the human prospects is the *Global Assessment Report on Biodiversity and Ecosystem Services* released by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019). Its litany of worsening problems ranges from the loss of coral reefs (about half of them gone since 1870) to

land degradation (reducing productivity on nearly a quarter of the global terrestrial area), and from the decline of pollinators to alien species invasions (up by 40% since 1980). The direst of all conclusions is that

an average of around 25 per cent of species in assessed animal and plant groups are threatened, suggesting that around 1 million species already face extinction, many within decades, unless action is taken to reduce the intensity of drivers of biodiversity loss. Without such action there will be a further acceleration in the global rate of species extinction, which is already at least tens to hundreds of times higher than it has averaged over the past 10 million years.

And it is not just marching teenage activists or the Extinction Rebellion but also the President of the UN's General Assembly who claimed that 11 years are all that remains to avert catastrophe ([UN 2019b](#)). We even get a view on the collapsed Western civilization from the future ([Oreskes and Conway 2014](#)), and [Bendell \(2018, 2\)](#) wrote his conceptual paper about the global climate tragedy in order “to provide readers with an opportunity to reassess their work and life in the face of an inevitable near term social collapse due to climate change.”

I find the recurrent catastrophism (be it climate- or resource-led) both wearisome and unconvincing—but I have a similar reaction to the opposite views of the future. The first, a relatively restrained version of these views, is one of an ever-better world, of promises that the coming generations will see many repeats of our recent accomplishments, replete with monotonously improving health, rising life expectancies, higher incomes, ever greater surfeits of food and energy, even more affordable mobility, and an even easier access to information—and all of that would be taking place with ever lower impact on the environment. This is the message of the two much acclaimed publications by Hans Rosling and Steven Pinker ([Rosling et al. 2018](#); [Pinker 2018](#)).

The authors have followed the same basic precept that I did in this book and in other writings since the year 2000 (most notably in Smil [2005](#), [2006](#), [2010a](#), [2013b](#), [2014](#), [2017a](#), and [2020](#)). All of us have assessed many remarkable historic achievements and appraised the current state of modern civilization by focusing on facts and numbers, past and present. All of us have pointed out many impressive quality-of-life gains and stunning technical accomplishments in order to explain—contrary to ubiquitous news headlines reporting on a variety of depressing problems and the

writings about imminent peaks, downturns, and catastrophes—how so much has gone steadily and impressively better.

In his *Factfulness* Hans Rosling (2018) argued that even well-informed people are getting “the basic facts about the world wrong,” that “the world is getting worse” is “the mega misconception,” that “things are better than you think.” Steven Pinker (2018, 77) admonished us to follow trend lines, not the headlines, and recited numerous quality-of-life gains ranging from longevity and reduction of poverty to the diffusion of democratic governance. I strongly agree with Rosling and Pinker that pointing out the extent and the rate of the past advances provides needed correctives to one-sided portrayals of the world mired in ever more intractable problems. But why am I not ready to share completely either Rosling’s or Pinker’s outlook; why I do not believe that the admirable record is the inevitable basis for seeing more of the same in the future?

I am not (choosing just a few of Pinker’s derogatory epithets) a “declinist,” I do not practice “progressophobia,” and most certainly I am not an “entrepreneur of mayhem”—but I have at least three major concerns with the message of general and unstoppable improvement. The first, and a readily documented, part of my unease is due to what I call selective inattention to facts. Both Rosling and Pinker chose to ignore realities that do not fit their claims, and they have done so even within the categories they selected to illustrate many admirable advances. Berggren (2018) offers a substantial critique of Rosling’s “biased selection of variables” and I will illustrate this point by just two key examples.

The Earth’s biosphere is hardly present in Rosling’s book: there is nothing at all about such key concerns as the loss of biodiversity, and global warming gets 14 lines in 329 pages of the text. And if Rosling’s book is “about the world and how it really is,” why does it say nothing about increasing inequality of income and wealth distribution? This is a curious omission in a book that was published four years after Thomas Piketty’s much publicized *Capital in the Twenty-First Century* (Piketty 2014). I am well aware that Piketty’s conclusions have been questioned—notably, Auten and Splinter (2018) had convincingly demonstrated that not all of his claims about the shifts in the United States withstand a critical inquiry—but many other recent studies have shown that inequality has been on the rise around the world, perhaps most notably in China.

The country has been invariably cited as the greatest success of spreading new wealth, and it has indeed moved most of its population from a mere subsistence to a modicum of prosperity—but (as already noted) the Chinese society has also moved from being moderately unequal in the early stages of the economic reforms during the 1980s to being one of the world’s most unequal countries (Jain-Chandra et al. 2017). While there are no references to this unwelcome economic shift among Rosling’s sources, he lists four of Pinker’s books, led by *The Better Angels of Our Nature* (Pinker 2011), whose basic message—that just about everything has gotten better and more of the same is ahead—has been reiterated and expanded in *Enlightenment Now* (Pinker 2018).

The most notable message of the first book was that violence has been declining, that wars between states, and hence battle deaths, have become rare. Again, others have provided thoughtful critiques of the underlying idea of the moral progress (Gray 2015) and of Pinker’s “extended flirtation with the utopianism” (Willick 2018), and I will point out only that a different metric tells a very different story. In this age of supposedly disappearing conflicts the United States has been engaged in the longest war in its history in its fight in Afghanistan, first against al-Qaida and the Taliban, then against the Taliban alone and eventually against the Taliban and ISIS. By October 2019 this war entered its 19th year with no military resolution in sight and with the Taliban being now a much more powerful force than it was in 2001, and any “peace” would be just a surrender to a medieval misogynic theocracy.

Moreover, by 2019 the cost of America’s wars in Iraq, Afghanistan, Pakistan, and Syria has reached nearly \$6 trillion, and future costs of interest on borrowed monies and of veteran care will push that to estimated \$8 trillion in the next 40 years (Watson Institute 2018). And, a fact that Pinker entirely ignored, more than 480,000 people have died in these wars, the total higher than the combined US military and civilian deaths in World War II (DeBruyne 2018). Such are the better angels? And other violent conflicts, from Mali to Myanmar, have hardly gone away and they are disproportionately affecting civilians. For that reason the UN High Commission for Refugees now reports that the number of forcibly displaced people in 2019 is the highest ever, totaling about 71 million worldwide (UNHCR 2019). And how would Pinker classify the new phenomenon of mass-scale incarceration (including nearly 2.2 million US adults)?

Pinker also cites several examples of notable environmental improvements—including the reduced emissions of US air pollutants, the reduced deforestation in temperate ecosystems, the decline in oil spills, and the worldwide increase of protected areas—and he even claims that the global rate of extinctions has been reduced by 75%. And yet [Pimm et al. \(2014\)](#) concluded that the current extinction rate is about 1,000 times the likely pre-human background, [Watson et al. \(2016\)](#) calculated that we have destroyed one-tenth of the Earth's wilderness in just two decades, and [Ceballos et al. \(2015\)](#) frame the accelerated human-induced species loss as the beginning of the planet's sixth mass extinction. If acknowledged, how could any of this be interpreted as progress?

My second, and a much more serious objection, is that these visions of endless automatic improvements of lives, environment, societies, and economies amount to simplistic escalators in the building whose floors never end. As [Pinker \(2018, 77\)](#) concluded, “the forces that have propelled progress—knowledge, prosperity, connectivity—will probably not go into reverse, and they build on one another.” This kind of determinism can be read as a profession of yet another belief, one leaving little room for discontinuities, reversals, and unpredictable shifts that have always marked the evolution of our species and its recorded history. A student of history might point out that while gains and advances have been real, cycles—rather than inexorable, unidirectional self-reinforcing trajectories—have been always a part of that history, and that “instead of becoming ever stronger . . . civilisation remains inherently fragile” ([Gray 2015, 6](#)). Or, as [McNeill \(1992\)](#) reminded us, we should not dismiss the conservation of catastrophe as a reality in human affairs.

And no serious student of growth would find it possible to believe that logistic or confined exponential growth curves have no place in the real world, which is supposedly composed of endlessly rising trends that follow not merely linear but exponential, and even hyperbolic, trajectories. These well-established convictions about accelerating growth got a powerful boost from the development of electronic capabilities that, we are promised, will soon have societies that will be governed by artificial intelligence and whose economic growth will be decoupled from rising needs for energy and materials. These claims belong to the second, and truly unrestrained, category of inevitably escalating progress.

In this world of never-ending advances there is no room for asymptotes and limits. This attitude has been carried most prominently to its extremes by Ray Kurzweil and, more recently, by Geoffrey [West \(2017\)](#) and Yuval [Harari \(2018\)](#). In extreme interpretation this would entail far more than continuous and vigorous growth: it would lead us to unimaginably rewarding futures:

So we won't experience 100 years of progress in the 21st century—it will be more like 20,000 years of progress (at today's rate). . . . There's even exponential growth in the rate of exponential growth. Within a few decades, machine intelligence will surpass human intelligence, leading to The Singularity—technological change so rapid and profound it represents a rupture in the fabric of human history. The implications include the merger of biological and nonbiological intelligence, immortal software-based humans, and ultra-high levels of intelligence that expand outward in the universe at the speed of light ([Kurzweil 2001](#), 1).

Humans a million times more intelligent and operating a million times faster would deliver a century of recent progress in a few milliseconds, and meeting the physical needs of humanity would be then trivial. That time is approaching fast: Kurzweil's latest forecast for reaching the Singularity is 2045 ([Kurzweil 2017](#)). Kurzweil has been joined by other believers in some kind of approaching singularity, and they come from different disciplines. [West \(2017\)](#) agrees that human activities will scale at super-exponential speeds, resulting in infinite quantities within a finite time, the state properly described by [Dyson \(2018\)](#) “as belonging to science fiction rather than to science.”

[Harari's \(2018\)](#) thinking is encapsulated in the very title of his book, *Homo Deus*. Undoubtedly, any serious historian must acknowledge that we have been a very adaptable, a very inventive, and hence a very successful species—but surely not a godlike one. Not a problem for Harari: his book presents a future in which the accomplished dream of immortality and divinity leads to godlike species commanding an omnipotent artificial intelligence that would make the bulk of humanity superfluous. Some economists, too, envisage quasi-miraculous transformations generated by never-ending innovation ([Mokyr 2014](#)).

And Ausubel believes that “resources are not needed. . . . Nature is useless, or nearly so, at least in a traditional market sense” and that

[h]umanity's goal is to render ourselves independent from the natural system . . . we will continue the shift, toward landless and vertical agriculture. . . . Cities will function essentially as closed systems where most materials, including water, will be recycled. . . . We will keep doubling our use of information every ten years, and that will liberate the rest. And within another 60 years we may smile, because our actual achievement will have been to achieve conservation by establishing an enduring trajectory of making Nature useless ([Ausubel 2015](#)).

If the preceding three paragraphs will have captured even a fraction of the coming reality, then all of our current concerns about the state of the economy (from deindustrialization to robotization), about the state of the biosphere (from global warming to ocean acidification), or about the challenges of caring for an aging population (from dementia to physical frailty) would be pointless. There is no need to worry; all we have to do is just to wait a few decades and then have everything taken care of by the arrival of inexorable, automatic super-augmentation of intelligence that will grow hyper-exponentially, reach infinite speed, make nature worthless, and turn (already godlike) people into super-gods.

But in the real world inexorably limiting trajectories always prevail in the biosphere, where the growth of individual organisms or the evolution of ecosystems are shaped and bounded by a myriad of natural constraints. And it should be never forgotten that our societies and economies are nothing but subsystems of the biosphere. This immutable hierarchy is critical in many ways, most fundamentally in maintaining suitable conditions for food production. In this respect, plant biodiversity and the health of bees have received plenty of public attention, but the dependence goes far deeper.

For example, unless we come up with an altogether different plant metabolism and deploy it in staple crops, growers of all crops will have to reckon with the fact that (as a result of plant evolution) nitrogen will be always the dominant macronutrient. Thus we cannot ignore either nitrogen's natural biogeochemical cycling (be it bacterial denitrification or leaching of nitrates) or the fact that staple cereals (unlike legumes symbiotic with N-fixing bacteria) cannot supply themselves with a reactive form of this essential element. This constraint might be overcome by extending nitrogen fixation capability to cereal and oil crops, but recent discoveries of some intriguing natural processes whose adaptation can contribute to that goal, perhaps most notably those by [Van Deynze et al. \(2018\)](#), remain in the realm of experiments and we have no idea to what extent would such symbioses reduce the prevailing crop yields.

This point brings me to the third and perhaps the most fundamental objection to the writings about constant and inexorable improvements and limitless prospects: their treatment of the biospheric degradation. Those writings take one of the three approaches. Some of them completely ignore enormous environmental burdens already exacted by the admirable quality-of-life advances. The second approach is to refer to them in passing and without expressing any concerns about the further intensification of these worrisome changes. The third way is to point out to some past successes in controlling emissions or extending environmental protection as useful templates for coming solutions.

For example, [Pinker \(2018\)](#) refers to declining intensity of CO₂ emissions per dollar of GDP and the post-1990 expansion of protected areas as major examples of past steps showing the effective solutions. But while those relative European, US, and global emissions of CO₂ peaked two to three generations ago, their absolute level has reached record heights; the global total, contrary to Pinker's claim, keeps rising—and the atmosphere responds (absorbs slightly more of the outgoing radiation) to the rise in absolute concentrations of CO₂, not to relative shifts in national contributions. And while the extension of protected land makes for nice ascending graphs, many natural parks are the places of frequent poaching (not only in Africa but also in Canada), illegal logging, and encroachment by settlements: realities behind claimed numbers are not as encouraging.

Much more worrisome is the fact that those who believe in ever-escalating inventions, those who impute godlike abilities to our species, and those who argue that we must make nature worthless are (largely or completely) unconcerned about the imperative to maintain a habitable planet and about the fact that this ultimate quest is incompatible with the continuation of an enormous range of changes that we have already inflicted on the biosphere. They do not appear to acknowledge the extent of these transformations, from already much evident massive loss of primary forests to bacterial resistance to antibiotics or from the potential transformations and impacts ranging from extraordinarily rapid melting of the Antarctic to viral pandemics.

Nowhere in their writings is a well-laid-out recognition that we have already seriously weakened the biospheric foundations of human existence, that the global environment has paid an enormous price for all those admirable quality-of-life gains, and that the intensity and the extent of these

impacts might be now reaching levels justifying the label of a new geologic era, the Anthropocene. Nowhere is an acknowledgment that this process has accelerated to such an extent that we are approaching several boundaries that should not be crossed in order to maintain the long-term habitability of the planet. We can keep undermining these foundations only for so long . . . and even if there is no sudden collapse the structure will eventually weaken to such an extent that it will begin to shift and that we will have to cope with very different conditions. These, indeed, are precisely the effects of continuing anthropogenic climate change, destruction and modification of ground cover, mass-scale urbanization, and giga-scale extraction of fuels and materials.

And the further environmental degradation is inevitable because billions of people (now five, soon to become seven) have yet to benefit from most of the gains enjoyed by the minority living in better-off countries and because (as I have shown) such gains require large (two- or three-orders of magnitude) gains in enabling inputs. Attempts have been made to define the Earth's safe operating space by specifying maximum loadings and flows ([Rockström et al. 2009](#); [Steffen et al. 2015b](#)) but because we do not fully understand the complexities of the biosphere's dynamics, such exercises remain indicative and informative rather than strongly predictive. But we can define the key requirements and quantify some essential demand ranges in order to explore the requirements and limits of the coming grand transitions.

What we need is not difficult to outline, and most of the list should be equally approved (albeit for different reasons) by free-market economists, energy innovators, or environmental activists. Most obviously, we need to do better than maintaining the current access to food: that access would require substantially increased output (or higher imports) in countries with a growing population and with existing chronic undernutrition and adequate incomes to assure the access to good nutrition. Similarly, we should increase per capita consumption of energy and materials in all low- and middle-income countries in order to run their economies at levels at least broadly compatible with a dignified quality of life. And all of these gains and improvements should be done in ways that put the modern civilization on a substantially less destructive environmental path. Reduced population growth would help to achieve all of those goals—but such help will not be

forthcoming anytime soon: during the first half of the 21st century the world will have added an equivalent of two Chinas.

And what has China done recently? In order to bring a modicum of prosperity to its nearly 1.4 billion people, in the 25 years between 1990 and 2015 China had increased its consumption of total energy more than fourfold; and of cement and steel, the two infrastructural foundations of modernity, 12-fold; and it now accounts for about 50% of worldwide output of steel and nearly 60% of cement production. Even just to extend China-like improvements to nearly half of the world's existing population (more than 3.5 billion people in 2020), whose level of economic development remains a fraction of the current Chinese level, would entail efforts that would require at least twice as much energy and material inputs as China consumes now. And the quest for economic development does not end when reaching China's recent level that is still less than half of per capita rates common in affluent countries. And, concurrently, the same benefits should be extended to more than three billion people who will be added in the world's poorest countries during the first half of this century.

How could these requirements be met without pushing even closer to the safe boundaries of human interference with the biosphere (and in several cases already past them!) and without accelerating rather than slowing down global warming? Recent advances in generating electricity from renewable sources, mostly by wind turbines and PV cells; relatively rapid adoption of electric vehicles in some countries; and the announcement of bold national plans for rapid transitions away from fossil fuels have raised many unrealistic expectations about the pace of future decarbonization.

Similarly, recent advances in genomics and genetic engineering have raised hopes for an early exploitation of designed organisms (synthetic species) whose commercialization could help us to solve challenges ranging from nutrition to material production. And recent ceaseless claims about the progress of artificial intelligence and the advent of the Fourth Industrial Revolution lead many to believe that future in which machines will make people redundant is imminent.

Such expectations have been affected by what I have called Moore's curse, a deeply mistaken impression that exponential gains in crowding the components on a microchip (begun in 1965 and still continuing) can be rapidly replicated in other fields of technical innovation, not the least by creating the world run totally on renewable energies, fed miraculously by

newly designed synthetic species, and governed perfectly by divinely intelligent machines. Unfortunately, that is a classic categorical mistake, as the brief doubling time for component density, corresponding to an annual growth rate of about 35%, has been a remarkable exception rather than the guide to the speed of general human progress. Much like all of its predecessors, modern civilization depends on constant flows of energy and materials, and the performance of processes and conversions that deliver these fundamental inputs cannot be doubling every couple of years.

The inputs' improvements show growth rates an order of magnitude lower than those due to Moore's law, ranging mostly between 1.5 and 3% a year (as do, with the opposite sign, annual energy, material savings, and cost reductions). Here are some important examples of these steady (and in the long term undoubtedly impressive) but modest improvement rates. During more than half a century since the introduction of short-stalked wheat and rice cultivars, average global yields of wheat and rice have grown, respectively, by about 3.2% and 2.6% a year, while the yields of American hybrid corn have been rising by 2%/year since 1950 ([FAO 2019](#)). During the 20th century the average efficiency of steam turbogenerators (producing most of the world's electricity) was improving by about 1.5% a year. Efficacy of lighting has been gaining annually about 2.6% since Edison's first light bulb. The energy cost of making steel, the defining metal of modern civilization, has been declining by less than 2%/year since 1950 ([Smil 2016a](#)). And the maximum speed of air travel has remained approximately constant since the beginning of regular jetliner service in 1958.

Rapid growth rates of unit capacities or annual installations of new products (ranging from wind turbines to electric vehicles) are often cited as proofs of new realities characterizing advances of a new era—but such relatively high rates are expected in early stages of growth when typical logistic trajectories are in their earliest, ascending phase: that is, before reaching their maximum growth rates that are followed by gradually declining gains. High rates had also characterized early introduction of locomotive speeds or steam-turbine capacities or radio ownership. Declining unit costs of new installations are also expected during the early stages of diffusion. Eventually the rates of all gains, be it the annual increase in the stock of new devices or the cost of new conversions, must decelerate.

But there is one fundamental difference between the energy and material needs of modern civilization and those of all of its predecessors: their unprecedented scale. Global power flows are now measured in terawatts; annual food demand and requirements for mineral and organic materials rate in billions of metric tons. Today's nearly 8 billion people turn out products and services whose annual value surpasses US\$100 trillion; this global economic system consumes primary commercial energy at the rate of about 18 TW (with 85% of the total coming from fossil fuels); its population consumes about 2.6 Gt of grain and about 300 Mt of meat, as well as some 60 Gt of building materials, metals, and synthetics. Given these scales, any alternatives to processes and industries that now provide these inputs would require considerable periods of time to be widely adopted even if such innovations were already technically mature and affordable. So how fast could the coming transitions unfold?

Notice the conditional verb in the last sentence: *could*, not *will*. I have to emphasize that this section's aim is not to offer any time-specific forecasts. I have avoided such efforts for decades—and have done so for obvious reasons: likelihood of any forecasts getting it right declines precipitously with the length of the forecasting horizon, and even if a long-range forecast comes close to capturing a specific trend it will not be able to anticipate its all-important broader setting. Given the ease with which long-range forecasts can be made by models fitting various growth curves or running more or less elaborate replicas of various systems, and given the widespread demand for such exercises, it is not surprising that the post-1960 decades have been littered with failed forecasts and that substantial books (both entertaining and depressing) could be written to illustrate this irresistible quest for irrelevance.

No human endeavor has been immune to these failures, and examples of enormous exaggerations, of failures to anticipate major shifts, of outright illusions and delusions abound in economic or energy forecasting as commonly as they do in predictions focusing on population, food, and the environment. Entertaining examples in the economic category include the forecasts of soaring stock market values based on the expansion of the 1990s. When the Dow Jones rose just above 11,000 points by the end of 1999, some forecasters saw it advancing rapidly and unstoppably not just to 40,000 ([Elias 2000](#)) but even to 100,000 ([Kadlec and Acampora 1999](#)). More than two decades later we are still less than a third below that level.

The most famous forecast failure concerning energy developments was a commonly shared expectation of nuclear fission taking over electricity generations by the end of the 20th century ([Smil 2017b](#)). This claim was made first during the 1950s and then persisted until the early 1970s, when forecasts envisaged not only mass-scale adoption of water-cooled reactors but also the switch to fast-breeder reactors. Reality checks: in 2019 fission generated only about 10% of global electricity and no breeders were in commercial operation. And we are still waiting for commercially viable nuclear fusion, for the global hydrogen economy, or for mass-scale production of inexpensive biofuels (cellulosic ethanol abundantly produced by designer enzymes). And the frequency of dubious claims has been increasing as we hear daily about new and supposedly “disruptive” inventions that work in principle or in lab-bench experiments but whose mass-scale deployment may come only after decades of gradual development, or may never take place at all. Such claims (often exceedingly bold as the inventors vie for investors with exaggerated promises) range from effective treatment for dementia to self-fertilizing crops to near-miraculous batteries.

Coming Transitions

Instead of such dubious forecasts I prefer to outline the most likely range of possibilities and opportunities that take into account inevitable technical constraints and biospheric limits, and that consider the likelihood of adoption and diffusion of innovations at scales making substantial difference. Our record of being able to separate truly promising innovations from hyped-up claims has been poor, and I do not see any reason that we should start suddenly excelling in this daunting challenge. Instead, I will note why the most promising claims that could be driving the coming transitions may take considerable time to become ubiquitous realities. This viewpoint might lead me to err on a conservative side but I remain unapologetic: better to be occasionally wrong but pleasantly surprised than being chronically disappointed.

Populations and food

Global population prospects had undergone a fundamental transformation during the last 40 years of the 20th century. During the early 1960s concerns about continued hyperbolic growth led to forecasts of an infinitely rapid expansion rate by 2026 ([von Foerster et al. 1960](#)) or, more realistically, to renewed Malthusian worries. [Heilbroner \(1975, 33\)](#) feared that by 2075 the underdeveloped world “will have to support something like 40 billion” people. Four decades later, the convergence of total fertility rates to below-replacement levels, first observed in Europe, became the norm in many modernizing countries of Asia and Latin America. Some of these countries have been at these low fertility levels since the 1970s and their experience shows only slightly fluctuating, essentially flat trajectories with no signs of any decisive reversals.

This fertility decline has been the main reason [Lutz et al. \(2001\)](#) concluded that there is an 85% probability that the world population will stop growing before the end of the 21st century and a 60% probability that it will not surpass 10 billion (they also assigned a 15% probability to the 2100 total being lower than in the year 2000). Obviously, this shift would eliminate population growth as a key factor in food and energy demand, in economic growth, and in a rising environmental deterioration with a stabilized population, resources could go toward raising the quality of life and the prospects for reversing the biospheric degradation would become more realistic (unless the stabilized population would strive for the levels of per capita consumption now prevailing in the United States or in Dubai). But it did not take long before this hope for a near-term end of population growth was disputed.

In 2014 the UN’s revision of the world population prospects (using probabilistic population projections) concluded that “there is little prospect of an end to world population growth this century without unprecedented fertility declines in most parts of sub-Saharan Africa” ([Gerland et al. 2014, 234](#)). The revision had the total growing from 7.6 billion in 2012 to 9.6 billion in 2050 and 10.9 billion in 2100 (with 95% probability that the 2100 total will be between 9 and 13.2 billion) and it concluded that the probability of the growth ending during the 21st century is no higher than 30%. The 2017 revision raised the medium forecast for 2100 to 11.2 billion ([UN 2017b](#)), but the 2019 revision brought it back to 10.87 billion ([UN 2019c](#)).

The main reason for the upward revisions has been the slowdown of fertility decline in Africa: it was decreasing during the 1990s but at only about 25% of the rate that was seen in Asia and Latin America during the 1970s when those regions were at a comparable stage of fertility transitions ([Bongaarts and Casterline 2013](#)). A total fertility rate higher than 3.2 (50% above the replacement rate) remains the norm everywhere in Africa but it is uncommon in more populous non-African countries: it prevails only in Pakistan, Yemen, and Bolivia ([Bongaarts and Casterline 2018](#)). A recent stall in Africa's fertility decline could be partly traced to disruptions in female education ([Kebedea et al. 2019](#)).

As a result, the future course of fertility transition in Africa remains highly uncertain: the UN's long-range prospect put the 95% probability brackets for African total in 2100 at 3.1–5.7 billion, with a median of 4.3 billion compared to just 1 billion in 2012. Moving, once again, in the opposite direction, the medium variant of a major alternative forecast prepared at the International Institute for Applied Systems Analysis assumed that advancing urbanization and education will reduce future growth rates, with the global total rising to 9.2 billion by 2050, peaking at around 9.7 billion around 2070, and then slowly declining to 9 billion by the end of the 21st century ([Lutz et al. 2014](#)). And a recent book claimed that an even faster retreat is possible, as the shock of global population decline will soon create an empty planet ([Bricker and Ibbitson 2018](#)). Such a drastic reversal is highly unlikely. Even according to the International Institute for Applied Systems Analysis (IIASA)'s reduced growth scenario, Africa's total, although 30% lower than the UN's medium forecast, would be still 3 billion in 2100.

The other notable set of findings in the UN's latest population prospect reports is that the old-age dependency ratios will see significant increases everywhere. Population aging, already so evident in Japan and in some European countries, will deepen and its most acute manifestations will be in China. China's population is now forecast to peak in 2029 at 1.442 billion, and then commence an "unstoppable" decline to 1.346 billion in 2050 and 1.172 billion (equal to the 1990 total) in 2065 (CASS 2019). For comparison, UN forecasts see the peak in 2031 at 1.464 billion and decline to 1.402 billion by 2050 ([UN 2019c](#)). As a result, the anticipated rise of the old-age dependency ratio for the entire 21st century would be most consequential in China, from just 11 to 64; that would be higher than

Europe's mean of 61 but still lower than Japan's rate of about 80. India's ratio would rise from 9 to 50, while in Africa it would increase from 8 to 24 and in Nigeria from less than 7 to 17 ([UN 2019c](#)). Fiscal implications of population aging will thus challenge not only all high-income countries but also China, Taiwan, South Korea, and Malaysia ([Cai et al. 2018](#)).

All of this means, first, that only an unprecedented decline of African fertilities could prevent continued growth of the global population during the 21st century, and we know that achieving low fertility at the aggregate level is impossible in the absence of highly prevalent and effective birth control ([Bongaarts and Casterline 2018](#)). Second, between 2020 and 2100 the global population will most likely grow by about 40% or by an additional 3.1 billion people, with roughly half of that gain in the world's poorest countries in Africa, a major reordering of the global population. Third, all societies will be aging, with old-age dependency ratios rising to about 60 in Europe and China and more than tripling even in Africa. By 2060 the global age-sex distribution (broad-based global population pyramids of the entire 20th century, a dome-like profile by 2015) will resemble a column tapering above 50 years of age. This transformation will be accompanied by a further decline of multigenerational families, by the rise of single-person households, and by more people dying alone.

Fourth, many affluent countries will continue to experience substantial nationwide or subnational population declines. In Europe this decline is already a major problem in Rumania, Bulgaria, Greece, Albania, Latvia, and Lithuania as well as in nearly all of the former East Germany, in western and northwestern Spain and in parts of Scandinavia. In the United States the retreat is most obvious on the Great Plains, throughout Appalachia, and in Montana ([Johnson et al. 2018](#)). Fifth, an increasing number of European countries (including Russia) as well as Japan will enter the second half of the 21st century with diminished populations: compared to the year 2020 these declines (in the absence of immigration) might be as large as 15% in Japan and Romania, 12% in Poland, and 7% in Russia ([UN 2019c](#)).

Projections for the year 2100 have considerable margins of error (low and high variants of the 2019 UN revision are 7.3 and 15.6 billion, a more than 2.1-fold difference) and that inexactitude is why I will look only on the most likely gains by 2050. Looking slightly more than a single generation ahead is a much less error-prone proposition because large shares of future

mothers are already with us and there is also less uncertainty in foreseeing the course of fertilities for just three, rather than eight, decades. The medium 2050 projection of 9.74 billion differs by less than $\pm 10\%$ from low and high variants—but the message of a surprisingly high burden of continued population growth remains the same.

During the second half of the 20th century the world added 3.61 billion people; during the first half of the 21st century the most likely gain will be 3.6 billion people, as slower growth rates and a higher base will result in virtually identical total increase. This gain will have major consequences for energy and materials required for the needed economic growth but, unless the environmental conditions rapidly deteriorate because of the continuing climate change (and these impacts are hard to quantify on the global level), several recent global assessments of future food production agree that it should not require any extraordinary measures to feed the population of nearly 10 billion ([Bruinsma 2009](#); [FAO 2009](#); [FAO 2017c](#); [Steensland and Zeigler 2017](#); [Searchinger et al. 2018](#)).

Major structural shifts due to aging, the shrinking size of households, and national or subnational depopulation will be accompanied by international migration. Flows from low-income countries to affluent nations may be slowed down by various countermeasures, but foreign aid is not an effective tool to deter emigration ([Clemens and Postel 2018](#)). Walls, patrols, and agreements with the source countries notwithstanding, in the long run Europe will see additional millions of newcomers from its Muslim hinterland, many millions of migrants from Central and South America will reach (legally and illegally) the United States, and most of the legal immigrants to Australia and Canada will continue to come from Asia and Africa. These movements will continue to be among the most effective (albeit socially disruptive) ways of reducing the inequality between the world's have and have-not countries.

By 2050 overall food demand might be up by about 60%, compared to the beginning of the 21st century, and the demand for animal foods might be as much as 70% higher. Annual harvest of staple grains would have to reach 3 Gt and meat production would have to rise to nearly 500 Mt. Combination of adequate investment, continued productivity improvements, intensification of cropping, extension of farmland, reduction of waste, and moderation of animal food intakes should be able to meet the needed targets. None of these factors needed inputs, and improvements

demand unprecedented rates and gains, but none of them should be allowed to fall below the trajectories that would increase supply while reducing the environmental input.

In the first place this action will require keeping the main driver of past and future gains, the global agricultural productivity index, averaging 1.75% a year. Only that rate would limit the need for further significant extension of farmland and pastures. Increased intensification of cropping would keep the additional need for cultivated land below 10% of the current total, all of it in low-income countries. Expansion of arable land should take place mostly in Africa and Latin America but, fortunately, several countries on these continents (Brazil, Argentina, Colombia, and Venezuela in South America; Congo, Angola, Mozambique, and Tanzania in the sub-Saharan Africa) have the highest potential for new cropping.

Productivity gains are best indicated by the yield gap based on plant growth models based on existing climate, soil, and water conditions (GYGA 2017). Even in the United States the nationwide yield gaps are 2–3 t/ha for both rainfed and irrigated corn and 3–4 for irrigated rice; Indian gaps are 1.6–2.4 for rainfed and 3.2–4 for irrigated wheat. As expected, nowhere is the yield gap as large as in sub-Saharan Africa, where traditional rainfed cropping is still often done with no or minimal fertilization. For corn, the staple in many African countries, water-limited yields are 12–13 t/ha in Ethiopia (compared to actual harvest of 2–3 t/ha) and 10–11 t/ha in Nigeria (compared to harvests of 1–2 t/ha). Narrowing these gaps has been long overdue: in spite of the enormous agricultural potential of Africa (particularly when compared to the two Asian megastates), the continent has been a net importer of staple cereals, dairy products, cooking oils, and meat since the 1970s ([Rakotoarisoa et al. 2012](#)).

Productivities should be also improved by the introduction of better crop varieties. The second half of the 20th century brought worldwide adoption of hybrid and short-stalked high-yielding grain varieties and also widespread cultivation of genetically modified corn and soybeans: in 2017 the United States planted 75 million ha of transgenic crops and Brazil was second with about 50 million ha (ISAAA 2017). Future contribution of these crops (as well as of genetically modified mammals and fish) remains difficult to predict, but there are other genetic improvements that could make, eventually, a major difference.

One of the most intriguing options is to design plants with minimized photorespiration, an essential metabolic repair pathway in oxygenic photosynthesis that carries a 20–50% yield penalty for common food and feed crops with a C_3 photosynthetic pathway ([Eisenhut and Weber 2019](#)). A synthetic pathway in transgenic tobacco plants tested by [South et al. \(2019\)](#) lowers photorespiration and it might eventually bring higher C_3 crop yields. But because the required enzymes are not present in natural genomes, any future crops possessing this advantage would have to be genetically engineered and hence their practicality is questionable.

Better agronomic practices should stabilize and reduce fertilizer use in affluent countries and there are no technical or resource obstacles to supplying adequate numbers of nutrients to the places with the highest yield gaps, above all to sub-Saharan Africa, where more intensive cropping will require substantial modernization of prevailing practices as well as advisory (extension services) and financial support. The ideal solution is the eventual introduction of nitrogen-fixing cereals, but the progress toward that goal has been disappointing. And it is even harder to envision how global agriculture could close the identified greenhouse gas mitigation gap, the difference between the annual emission originating in global agricultural and the target amount needed to limit the warming to less than 1.5°C. Emissions worth more than 10 Gt of the CO_2 equivalent—with large shares coming from CH_4 (from rice fields and ruminant animals) and N_2O from bacterial denitrification ([Bennetzen et al. 2016](#))—would have to be more than halved by 2050.

Substantial improvements are also possible in animal husbandry. For example, in 2015 India produced 50% more milk than the United States but it had ten times as many milk-producing bovines (cows and water buffaloes). And the most significant reduction of demand for feed grain would come from higher grain-to-meat conversion efficiencies in low-income countries. Alternatives to meat include growing animal muscles in bioreactors and producing meat-like substitutes based on plant (legume) proteins. The first path is unlikely to make an early large-scale difference. Eliminating as much methane as is now annually cut by gradual decline of American beef eating (down 31% since its peak in 1976) would necessitate setting up and operating meat-growing operations whose annual output would have to be about 50 times larger than the world's entire antibiotics

industry, currently the largest industry using bioreactors to grow new biomass.

How likely is it that such an industry could arise in three decades? On the other hand, legumes (above all soybeans and peas) are already used as sources of protein to produce meat replacements and larger volumes of pulses, now used in animal feeding, could be easily diverted into producing legume-based meat alternatives, particularly those for which texture is not an important consideration (replacing ground meats). My preference is for the rationalization of the existing animal production. I have demonstrated that we could provide enough animal protein for 10 billion people even when we are producing less meat and without any meat alternatives. This change could be effected by limiting consumption of beef just to the meat produced by grazing the animals or feeding them only crop residues and by expanding consumption of efficiently produced chicken, aquacultured fish, and dairy products ([Smil 2013b](#)).

Future food demand will change little or decline in many EU countries and it will decline in Japan. But Japan might not lower its import dependence, because its declining food demand will be accompanied by continuously decreasing number of farmers, already down by 25% between 2010 and 2017, with the average age approaching 70 years ([SB 2020](#)). In contrast, there will be the need for substantially higher food supplies in India and in African countries. As already noted, during the first half of the 21st century the world will, most likely, add the same number of people as during the second half of the 20th century, but nearly half of it will come from Africa, mostly from its sub-Saharan part (Casterline and Bongaarts 2017). This increase will present specific challenges for assuring adequate food supply.

As recently as the mid-1990s there were concerns about China's ability to feed itself ([Brown 1995](#)). Such speculations were based on mistaken assumptions and that the combination of "better management, better pricing, better inputs, and better environmental protection can extract enough additional food from China's agroecosystems to provide decent nutrition during the next generation" ([Smil 1995](#), 813). That combination is exactly what happened, and when we consider its relatively recent history of famines, food shortages, and starvation, China has done a remarkable job in meeting its food requirements ([Yu and Wu 2018](#)). I am no less confident that China can manage to feed itself in the future, a challenge made easier

by the fact that between 2019 and 2050 the Chinese population should actually decline slightly (by about 4%).

Improved agronomic practices should be able to assure continued provision of what is now a more than adequate food supply for the country's population without any substantial increases of its current food imports (in 2016 they amounted to less than 4% of cereal consumption). This conclusion is based on the post-1980 performance of China's agriculture as well as on a recent large-scale field study that demonstrated the possibility of producing more staple grains with lower environmental impacts ([Chen et al. 2014](#); [Cui et al. 2018](#)). This study of enhanced integrated soil-crop management practices was conducted between 2005 and 2015 and it was based on relevant crop ecophysiology and soil-biogeochemistry findings in China's major wheat-, rice-, and corn-growing areas.

The recommendations were eventually tested by 20.9 million farmers on staple grain areas covering nearly 40 million cumulative hectares. Average yield grains increased by about 11% and they were combined with 15–18% declines in nitrogen fertilizer applications and hence with reduced losses of reactive nitrogen. If most of China's farmers could realize most of these gains, the resulting harvests would be more than sufficient to supply enough grain for direct consumption as well as the demand for animal feed. In addition, as in the case of other aging populations, it should be expected that the overall demand for meat should eventually begin to decline, easing the demand for feed grain.

In absolute terms, no other country will thus face a greater challenge feeding its population in the coming decades than India, which will have some 600 million people more in 2050 than it had in the year 2000. Compared to China, India has a larger area of arable land (nearly 50% higher in per capita terms) and a larger volume of available water as well as generally larger yield gaps and lower use of fertilizers (nitrogen per hectare averages less than half of China's rate), a combination offering greater opportunities for the intensification and productivity growth ([Prajapati and Dutta 2014](#)). On the other hand, India still has a relatively larger share of undernourished people; its average supply of high-quality (animal) protein is less than half of China's mean; the rising demand may create significant supply gaps for legumes, cooking oil, and sugar; and the country will

always remain vulnerable to any major disruption of the monsoon regimes and to the reduced water flows from the Himalayas ([Maurer et al. 2019](#)).

While the world's two largest countries should be able (with some moderate imports) to meet their food demand until the time when their populations peak and begin to decline, it is hard to be confident that the food security in the Sahel will improve decisively. Most of the region's countries (including Mauritania, Mali, Niger, and Chad) have never eliminated acute malnutrition, their food self-sufficiency ratios have declined in recent decades, and even relatively modest decline (or increased variability) of precipitation would have (especially when coupled with chronically poor governance) serious impacts. The global scale of the challenge remains daunting: in 2016 there were still some 815 million undernourished people, about 155 million children under five years of age were suffering from stunted growth, and slightly more than 52 million children under five years of age were affected by wasting ([FAO 2017a](#)).

And food insecurity amidst the global sufficiency is not limited to the Sahel. According to [Fader et al. \(2013\)](#) 66 countries were not able to be self-sufficient in food because of natural resource constraints (limited availability of cropland and water) and their increasing populations will have to rely on the steadily expanding global food market. But here the prospect is more encouraging, thanks to an impressive reversal. Czarist Russia was a major grain exporter, while the notoriously inefficient Soviet agriculture could not adequately feed the country's population and by the late 1960s it had to resort to large grain imports. But that trend has been, finally, reversed. In 1990 the collapsing USSR accounted for 0.7% of the world's cereal export, by 2016 Russia's share rose to nearly 8%, and in the marketing year 2017–2018 Russia became, with 32.4 Mt, the world's largest exporter of wheat ahead of America's 31.5 Mt ([FAO 2019](#)). And the country, as well as its two largest neighbors, Ukraine and Kazakhstan, has a considerable potential for even larger harvest.

I must also stress the benefits that would follow from the global reduction of overweight and obesity to pre-1970 levels (a shift that would have no conceivable negative consequences) and from at least halving the worldwide food loss (a realistic long-term target that would still leave 20% of all food wasted in North America and Europe). Japan has been setting a perfect example of what might be possible and what benefits would accrue for other aging populations in affluent countries. Between 2000 and 2015

the country's average per capita food intake (for persons older than one year) has declined by 3%, animal foods now supply only about 25% of all food energy (SB 2020) while the country maintains its global primacy in life expectancy.

Recent worldwide appraisals of long-term food prospects are fairly encouraging in terms of potential output—but major concerns arise when these outputs are related to environmental factors. Springman et al. (2018) calculated that in the absence of innovative advances, environmental effects of expanded food production would increase by 50–90% between 2010 and 2050, reaching levels beyond the planetary boundaries that delimit a safe operating space for humanity. Rizvi et al. (2018) concluded that if feeding the world were to adhere to American dietary guidelines then the global food production with current agricultural practices would require an additional 1 billion ha of land (roughly equal to the entire territory of Canada). But currently about 36% of all energy produced by food crops is fed to animals, and biofuels claim about 5%. Cassidy et al. (2013) calculated that growing crops exclusively for direct human consumption would, theoretically, increase the available food energy supply by 70%, allowing for feeding an additional 4 billion people, more than the total projected by the UN's medium-version population forecast.

The EAT–Lancet Commission on food in the Anthropocene quantified the extent of agronomic and dietary changes that would be necessary to eliminate unsustainable production of unhealthy food and replace it with healthier, environment-sparing practices by 2050 (Willett et al. 2019). Dietary shifts would have to include more than a 50% reduction in global consumption of red meat and sugar, and a greater than 100% increase in consumption of nuts, fruits, vegetables, and legumes. And all of this should be done without using any

additional land while safeguarding existing biodiversity and reducing uses of water, nitrogen and phosphorus and limiting greenhouse gas emissions.

How challenging (or how unrealistically ambitious) such a relatively rapid and extensive transformation would be could be judged by comparing its requirements with a wider global assessment of needs needed to secure “a good life for all within planetary boundaries” (O'Neill et al. 2018). That appraisal concluded that basic physical needs (adequate nutrition, sanitation, access to electricity, and the elimination of extreme poverty)

could be met for today's more than 7 billion people without transgressing planetary boundaries—but reaching higher qualitative goals would require resources two to six times larger than the sustainable level based on current relationships.

Decarbonization of energy supply

Modern global civilization could not have been created without the transitions from traditional biomass energies and animate power to fossil fuels and inanimate prime movers powered by their combustion. This period of high dependence on fossil carbon began in the early years of the 20th century when coal began to supply more than half of the world's primary energy. A century later traditional biofuels provided only about 10% of the total and fossil fuels accounted for 90% of the rest (with the remainder coming largely from hydro- and nuclear generation). The onset of the fossil fuel era is thus very recent and in the absence of any environmental concerns its duration would be limited by the mass of fuels that could be profitably extracted from the topmost layer of the Earth's crust.

Available estimates of total resources in place are nothing but crude indicators of possible magnitudes, but they are useful in order to indicate the inevitably limited duration of the fossil fuel era. Even if the total fossil fuel resources were as high as 200 ZJ and even if eventual technical advances made it possible to recover all of them (that is, if all resources in place would become commercial reserves, a quite unrealistic assumption) at the current rate of extraction the era would have less than 500 years to go, no more time that has elapsed since the rule of Ivan the Terrible or Mary Queen of Scots and no more than a tenth of the entire span of the recorded history. While it was always clear that eventual advances in commercializing non-fossil energy conversions would leave most of the remaining fossil fuels in the ground, such a gradual transition determined solely by cost considerations now appears to be unacceptable.

We are now trying to shorten the fossil fuel era not because of any imminent concerns about running out of resources or because of unbearably high costs of their recovery and use. Not so long ago a vocal peak-oil movement forecast an imminent end of the oil era, but these were unfounded concerns. A combination of horizontal drilling and hydraulic

fracturing opened oil shales, a previously unexploitable resource, to mass-scale commercial recovery and, despite increasing demand, the world has experienced problems stemming from record crude oil production (with the United States once again in the lead), saturated markets, and falling crude oil prices.

The ultimate goal of the unfolding transition is easily stated: to satisfy the world's energy requirements without burning any fossil fuels. This is often called, incorrectly, the decarbonization of global energy supply. The goal is to avoid any additions of CO₂ from fossil fuels, but biomass fuels (on a dry basis about 50% carbon) could be used because carbon released by their combustion would be removed from the atmosphere by subsequent crops or tree plantings. And, a further complication, even some fossil fuel combustion might be allowed as long as there is no net addition of CO₂ to the atmosphere, a goal that could be achieved by enhanced sequestration of the gas (be it by mass-scale reforestation or by its capture and storage). The enormity of the global shift away from the fossil carbon is readily illustrated by reviewing the basic realities (Smil [2016c](#) and [2017b](#)).

First, we remain an overwhelmingly fossil-fueled civilization that has been recently running vigorously *into* fossil carbon rather than moving *away* from it. Between 1750 and the year 2000 anthropogenic global emissions of CO₂ from fossil fuels rose by three orders of magnitude to 7 billion metric tons of carbon, and during the first 17 years of the 21st century they grew by nearly 45% (Olivier and [Peters 2018](#); CO₂ Earth 2019). The share of fossil fuels in primary energy supply fell from about 98% in 1950 to 90% in the year 2000 (thanks to the expansion of hydro- and nuclear electricity generation) but their absolute consumption rose 5.3 times. And during the first 18 years of the 21st century total primary energy use, largely because of China's economic expansion, grew by almost 50%, the share of fossil fuels remained flat (about 85% according to BP, about 90% by using UN's conversions), and record volume of fossil carbon (about 9.2 Gt) was returned to the atmosphere as CO₂ ([BP 2020](#); LeQuéré et al. 2018). Moreover, nothing indicates any rapid reversals.

The direct effect of the COVID-19-driven decline of CO₂ emissions will be negligible ([Forster et al. 2020](#)), and even if the pandemic experience were to accelerate the energy transition in affluent countries it will not have a similar effect in today's low-energy economies. During the first two

decades of the 21st century, consumption of all primary energy remained flat in Europe; it was up only about 5% in North America, but the global aggregate has been growing by more than 2% a year, driven by Asia and Africa (BP 2020). As for the leading modernizing economies, Chinese forecasts expected that energy consumption will peak during the late 2020s, and then in 2035 (at about 158 EJ); the latest version delays the peak year to 2040 at 170 EJ, about 30% above the 2017 level (CNPC 2017). And according to a government study India's total primary energy consumption is expected to increase nearly fivefold between 2012 and 2047 (Kumar et al. 2017).

Long-range forecasts reflect these expectations, and even IEA's New Policy Scenario (which includes policies and targets announced by governments, as opposed to business as usual) foresees that by 2040 the global energy demand would be about 25% above the 2017 level (IEA 2018b). As in the past, electricity demand will grow faster than the overall primary energy supply, driven by the need to connect nearly a billion people who still do not have electricity as well as by strongly rising demand for air conditioning, in the manufacturing sector, in transportation, and for electronic devices (IEA 2018a). In IEA's New Policy Scenario, the demand in 2050 would be about 50% above the 2017 level, and the Future is Electric Scenario would require a further increase equivalent to combined 2017 consumption in China and India (IEA 2018b).

Second, large-scale energy transitions have been always gradual, prolonged affairs unfolding across generations, and the shift from fossil carbon to non-carbon energies will be no exception (Smil 2017b). The best way to illustrate the pace of this transition is to look at a quarter century of the global effort. The first global-warming-related treaty, the United Nations Framework Convention on Climate Change, was adopted in May 1992 with the objective to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UN 1992). The meeting coincided with the beginning of a strong (and often heavily subsidized) push to adopt renewable energies and hence we now have a significant period of time to appraise the unfolding transition from fossil fuels to renewables and to come up with some interim observations and conclusions.

When using the UN's energy conversions (1kWh of non-thermal electricity equal to 3.6 MJ) in order to calculate the aggregates of primary

energy that are needed to find specific shares, we see that in 1992 the world derived about 91% of its total primary energy from fossil fuels—and that the share was about 90.5% in 2017, essentially no change, no progress toward any global decarbonization. True, contributions of renewable energies grew significantly during those 25 years, but the consumption of fossil fuels grew so strongly that they maintained their overall share of the global supply and their global extraction was 53% higher than in 1992.

The key conclusion that needs repeating is that we have been running into fossil carbon, emitting 57% more CO₂ from combustion in 2017 than in 1992; as a result, the average tropospheric concentration of the gas increased by 14%, from 356.5 to 406.5 ppm (NOAA 2019). During the same time, contributions by wind turbines and PV cells were rising fast, from the combined total of only about 5 TWh in 1992 to 1565 TWh in 2017. That is a 300-fold increase in 25 years, not an uncommon rate for systems in early stages of growth—but in relative terms their share of total electricity generation rose to only about 6% in 2017, still far behind hydrogeneration with 16%.

Even if the combined share of wind and solar electricity triples during the next 25 years it might still remain smaller than that of the still expanding hydrogeneration and (depending on the uncertain future of nuclear industry) fossil-fueled generation might still account for more than half of the total by 2040 (in 2017 its share, mostly from coal and natural gas, was 68%). And when this wind and PV electricity was converted to a common energy denominator by using standard UN factors it supplied only 1.1% of all primary commercial energy in 2017, and after adding modern biofuels to wind and solar electricity generation the combined share of all new non-carbon energies was just 2.2% of the global primary energy.

Third, the shift toward renewable electricity generation is (relatively) the easiest part of the global energy transition, but while some countries now generate large shares of their demand from wind and solar PV, achieving a completely carbon-free electricity supply is a different matter. We have already mastered and considerably scaled up the key requisite conversion techniques: PV installations range from house rooftops (10³ W) to massive farms (with capacities of 10⁸ W), the largest central-power solar stations have the same capacity, and the largest operating offshore wind turbines have capacities of 10 MW. Moreover, unit costs of these installations have

been declining while their (inherently limited) capacity factors and efficiencies have been rising. But even these achievements are problematic.

One of the most common arguments used to illustrate the superiority of modern renewable electricity generation has been the falling costs of PV panels and wind turbines, now so low that in some places they are already by far the least expensive choices for new capacities. States that generate the largest shares of electricity from wind and solar should thus have low and falling electricity price—yet the very opposite is true. This paradox is explained largely by two realities. First, studies have shown a decline in the market value of intermittently supplied renewable energy at higher levels of penetration due to oversupply during periods of abundant sun and wind, a phenomenon already leading to negative prices ([Hirth 2013](#)). And systems with rising shares of renewable generation still have to maintain sufficient reserve capacities available to generate on demand.

Large-scale electricity storage would be the best way to boost the adoption of intermittent electricity generation but, so far, our effective centralized battery storage options go only up to 10^6 W, with discharge time of several hours. Decentralized options, so often touted by proponents of renewable generation, remain utterly impractical for large cities that house an increasing share of humanity. Tokyo's Major Metropolitan Region has about 39 million people and its electricity requirements are on the order of 30 GW. Supplying the region from storage just for three days during a major typhoon (when heavily overcast skies and strong winds would preclude any solar and wind generation) would require about 2.2 TWh ($30 \text{ GW} \times 72 \text{ hours}$). Even when we assume average levelized costs of commercial, industrial and residential storage at \$200/kWh ([Lazard 2018](#)) would mean that installing sufficient number of Li-ion storage units throughout Tokyo's metropolitan region in order to meet just a three-day electricity demand would cost nearly half a trillion dollars ($2.2 \text{ TWh} \times \$0.2/\text{Wh}$).

The only commercially available and cost-effective choice to store electricity at GW level is the pumped hydro storage, first introduced before the end of the 19th century. Its operation requires specific terrain configuration in order to place a low-lying reservoir close to a storage on top of a nearby mountain and achieve a substantial height difference, and it entails substantial (about 25%) energy loss due to uphill pumping. Cheaper nighttime electricity is used to pump water uphill and discharge it during

peak demand hours, but, obviously, the uphill pumping could be done by using solar or wind power during sunny and windy hours. No other energy storage options now under development (compressed air, flywheels, supercapacitors, flow batteries) will be able to deliver storage at GW level in the near future. Using hydrogen would solve many of these problems but that would require transition to a new hydrogen economy with the gas becoming a common energy carrier in industrial uses and in surface transportation.

Fourth, the transition to renewables will be much more difficult in transportation. Even in the United States, with its abundance of farmland and its ability to divert about 40% of corn from animal feed, the annual output of ethanol is equivalent to only 10% of gasoline consumption ([USEIA 2018b](#)). Global output of ethanol and biodiesel was just 95 Mt of oil equivalent in 2018, only about 3% of the current demand for all mobility needs, and any rapid order-of-magnitude expansion of these biofuels is most unlikely, because two-thirds of their recent output come from just two countries, the United States and Brazil. Production of cellulosic ethanol would expand the resource base but the actual performance of this new stream has lagged far behind the overenthusiastic expectations: in 2018, after years since launching the first plant, the US output of cellulosic ethanol was equivalent to less than 0.1% of corn ethanol ([Schill 2018](#)) and hence less than 0.01% of US gasoline demand, a reality that excludes any major near-term role of this fuel.

Conversions to electric drive is the best way to reduce the need for biofuels in the transportation sector. Mass-scale electrification of passenger vehicles faces no insurmountable technical problems but it will be accompanied by many new environmental challenges. They will range from the impact of mining needed to secure lithium, cobalt, nickel, and other elements required for mass-produced batteries to difficulties of battery recycling ([Dominish et al. 2019](#); [Kalgathgi 2018](#)). And, depending on the origins of electricity, electric cars may actually emit more CO₂ than diesel-powered vehicles: life-cycle analysis confirms that this has been the case in China ([Yu et al. 2018](#)).

As in many other cases of early adoption, sales of electric vehicles have been rising rapidly but even so, in 2020 less than 1% of motor vehicles on the road were electrics and, as already noted, it is highly unlikely they will be dominant even by 2040. Electrification of trucking based on current, or

gradually improving, batteries is far more challenging and, most importantly, we have no ready substitutes either for powerful diesel engines used in ocean shipping in bulk carriers, tankers, and container vessels moving all kinds of consumer goods, or for kerosene-powered turbofan engines in flight at a time of rapid expansion of intercontinental flying.

The huge gap between the respective energy densities prevents the adoption of batteries in shipping and flying. Refined fuels have energy density of nearly 12,000 Wh/kg (about 42 MJ/kg), the best commercially available Li-ion batteries rate on the order of 300 Wh/kg (about 1 MJ/kg), more than a 40-fold difference. At takeoff a Boeing 787 carries a maximum of about 101 t of kerosene and its total weight is 254 t, while even at 500 Wh/kg (if we assume a major density gain) batteries for the same flight would weigh nearly 2,500 t, or ten times the takeoff weight in 2019. Analogical comparison explains why container ships bringing consumer items from China to the European Union and North America will not be battery powered anytime soon ([Smil 2019b](#)).

Fifth, as challenging as it will be to displace carbon from all forms of transportation, the most difficult task will be to replace fossil carbon in many industries. Fuels used in some industrial processes (including pulp and paper, some chemical processes, and glass and pottery) could be completely or largely replaced by electricity (Schüwer and Schneider 2018). But these industrial processes require a constant and reliable supply of electricity, and hence a system entirely reliant on intermittent sources would have to be backed up by considerable storage capacities. And what is technically possible often remains unaffordable, given the current cost of natural gas (the prime choice for industrial heat requirements) and electricity: prices of the latter are typically three to five times more expensive per unit of energy.

In other sectors (above all in refineries, in chemical syntheses, and in ferrous metallurgy) only a much smaller share of currently used fuels could be replaced by electricity—yet these sectors produce the material keystones of modern civilization. Smelting of primary iron (in blast furnaces charged with iron ores, coke, and limestone) now produces about 1 Gt of the metal a year to be turned into steel needed for infrastructures, transportation, and industrial and consumer products. Blast-furnace smelting requires metallurgical coke, and the only commercial alternative that is now available on a relatively large scale is the direct reduction of iron—but that

process also requires carbon inputs in the form of natural gas. Similarly, we have no readily available mass-scale alternative to the use of petrochemical feedstocks in synthesizing annually nearly 200 Mt of ammonia and about 300 Mt plastics ([Smil 2018](#)).

The final point concerns the scales of the challenge, the magnitude of the system to be displaced, and the necessity for acting on the global scale. Even if non-carbon alternatives were readily available for affordable, mass-scale commercialization, we must remember that the world's carbon-based energy system constitutes the most extensive and the most expensive investment undertaken by our civilization. The system begins with the annual extraction of about 10 billion metric tons of fossil carbon, which are distributed by a combination of some 3 million kilometers of oil and gas pipelines, by hundreds of thousands of kilometers of railways as well as by about 10,000 oil and LNG tankers.

In 2019 fossil fuels still provided nearly 85% of all modern primary energy supply; their combustion is used to generate more than three-fifths of the world's electricity and to heat homes of about one billion people in Eurasia and North America; they supply more than 95% of energy for land-borne, water-borne, and air transportation (electric trains and automotive biofuels being the only two non-carbon exceptions); and they provide indispensable energy and raw materials for the production of the four material pillars of modern civilization: iron, cement, plastics, and ammonia. The replacement cost of the structures, infrastructure, and converters comprising this immense global system is most likely in excess of \$30 trillion.

The combination of the mass, complexity, and spatial extent of this global system and of the cost of equally reliable and affordable alternatives (even if they were fully available for mass-scale deployment) makes it obvious that its complete displacement will be a multigenerational task, and its success (however rapid or remote) depends on the sustained decline of atmospheric CO₂. This shift is predicated on global effort. Post-1950 national efforts were highly effective in cleaning water or reducing air pollution—but even if such major economies as the United Kingdom or France became carbon-free overnight, fossil-fuel-based global economic growth would replace those emissions in a single year. Between 2010 and 2018 the annual global increase of emissions from fossil fuels and cement averaged nearly 340 Mt CO₂, compared to the French output of 331 Mt and

the British release of 368 Mt (GCP 2019). In view of these realities any projections of sudden reversals followed by halving the CO₂ emissions by 2030 and then eliminating them by 2050—such as those posited in the IPCC’s report on 1.5°C warming (IPCC 2018) or outlined as emergency measures in Lenton et al. (2019)—are nothing but wishful thinking (Figure 7.3).

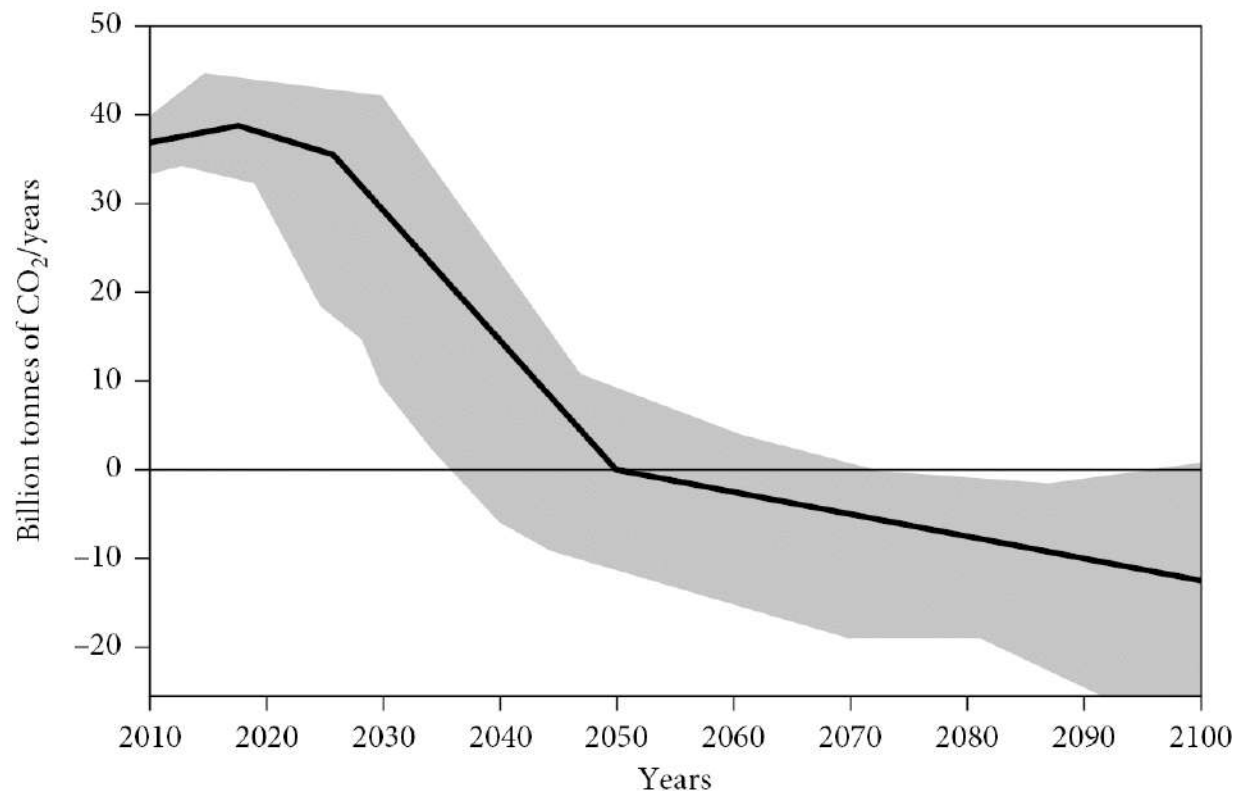


Figure 7.3 Wishful thinking: magically bending curves of various model pathways suggested by the IPCC (2018).

Because we are still in the very early phase of the transition to a non-carbon system, we cannot be sure what will be its eventual makeup, and what will be the eventual contributions of renewable and nuclear electricity, hydrogen, and biofuels. We know what its principal characteristics should be: acceptable cost; easy convertibility (that is, efficient and flexible transformation into desirable end-use forms of energy); convenient transportability; good energy return on investment; minimized environmental impact; high level of safety and reliability; and widespread public acceptance (Tsao et al. 2018; Smil 2017a; Hall et al. 2014). But it is

far too early to tell if the closing decade of the 21st century will be decisively dominated by electricity (a shift that would be facilitated by future advances in high-energy-density electricity storage) or if we will have a hydrogen-based economy.

Economies and the environment

This may be an apposite place to stress that in order to make better decisions we need better measures of economic activity as well as of energy use, the key driver of prosperity. The quest for a better economic indicator has some prominent advocates ([Stiglitz et al. 2010](#)) and the Human Development Index (HDI) has been the first widely used alternative (UNDP 2018). HDI is a composite that aggregates national scores for three dimensions (a long and healthy life, being knowledgeable, having a decent standard of living) but it is not concerned with inequality, poverty, and human security. The World Economic Forum now publishes its Inclusive Development Index (IDI), which measures how countries perform on 11 dimensions of economic progress in addition to their GDPs (WEF 2018). Its three pillars are growth and development, inclusion, and intergenerational equity (including sustainable stewardship of natural and financial resources).

Neither of these indices deals with environmental degradation that obviously detracts from quality-of-life gains, but a proposal by [Daly and Cobb \(1989\)](#) to include it in the per capita Index of Sustainable Welfare (ISEW) was never developed into an accepted tool. And a truly representative index should also account for dis-services caused by economic growth, perhaps along the lines suggested by Simon Kuznets before WW II ([Kuznets 1937](#)). His short (and obviously arguable) list of such dis-services, common in all modern acquisitive societies, included all military expenses, most outlays on advertising, costs of many financial and speculative activities, and, most importantly, those outlays on our urban living (such as extensive transportation or expensive houses) that became necessary in order to cope with the modern world's difficulties and that amount to costs implicit in our civilization. Kuznets was aware that such adjustments would be difficult to make but he was convinced that they “would make national income totals much better gauges of the volume of

services produced, for comparison among years and among nations” ([Kuznets 1937](#), 37).

As for energy, the standard comparisons of gross primary energy use (total and per capita) tell us nothing about the composition of the aggregate measure (fuel shares, importance of electricity), conversion efficiencies (actual usefully deployed energies), access to energy services, and controls used to reduce environmental impacts of energy use. Nearly all of these measures are available individually but it would be better to assess national progress on the basis of a representative energy index. Since 1999 an analogical index has been available for assessing national environmental progress, first as the Environmental Sustainability Index, then as the Environmental Performance Index (EPI 2019). Its objective is to quantify environmental health (risk exposure, air pollution, water, and sanitation) and ecosystem vitality (water resources, nitrogen balance, forests, fisheries, protected areas and species, and carbon emissions).

My look at unfolding economic and environmental transitions will differ from the coverage followed in the preceding sections. The section on the coming population and food transitions focused on the likely trajectories of two closely linked processes with clearly constrained outcomes. The section on the unfolding transition from fossil energies to renewable sources emphasized the inherent difficulties of this gradual shift, above all the enormous scale of the challenge and its many technical and economic complications. This section on the coming economic and environmental transition will have a clear normative component: it will address the key failures of the prevailing approaches to economic growth and environmental management and offer suggestions for some desirable improvements.

The starting point is the critique of the dominant economic thinking that has marginalized (and often ignored) the multitude of energetic, material, and environmental preconditions (enabling factors) that have made the grand transition to modernity and the ensuing quality-of-life gains possible. Moreover, its implicit understanding is that these inputs are not primary variables but merely some secondary requirements that could be conjured at will (and without any worrisome environmental impacts) by never-ending inventiveness of *Homo deus* accelerating toward the Singularity. One might say this is a mind over matter (and energy) approach to reality.

Economists have their list of factors responsible for economic growth: labor input, capital, education, improved allocation of resources, economies of scale, and the growth of knowledge. Where is energy and the environment? Energy is almost always absent; environment appears sometimes, merely in passing. For example, Robert Solow recognized “investment in environmental improvement, which uses resources but does not appear in measured output, though it may of course be very valuable” as a factor that has reduced the growth of economic output ([Solow 1987](#)).

As a scientist cognizant of energetic and material constraints on everything taking place on this planet I marvel at this disregard—and at the arguments that energy and the environment can be increasingly ignored, the notions expressed in currently fashionable talk about decoupling energy and economic growth and about dematerialization of future economies. The unfolding economic and environmental transition cannot succeed unless we recognize the central role of energy and materials and the importance of numerous environmental constraints in human well-being, and unless we come up with fundamentally different approaches to reconcile these imperatives with long-term economic development.

Believing that vigorous economic growth can proceed with ever smaller amounts of energy materials is a serious categorical mistake because such a decoupling would contravene fundamental physical principles. As already noted, the mainstream economic thought has comprehensively ignored the essential truth “that energy is the stuff of the universe, that all matter is also a form of energy, and that the economic system is essentially a system for extracting, processing and transforming energy as resources into energy embodied in products and services” ([Ayres 2017](#), 40). Origins of this omission are clear: because energy accounts for such a small share of economic output it can be ignored, or it could be seen just as a kind of man-made capital.

The history of energy conversions is the history of successful, gradual reductions of relative energy intensities, be it in terms of performance (energy/distance), embodied input (energy/mass of a final product), or overall cost (energy/\$ of an economic product). Similarly, the history of technical advances is the history of relative reductions of material needs, be it expressed as embodied inputs (mass of a specific material/unit of a final product) or in terms of overall costs (mass/\$ of a final product). But these welcome realities have three corollaries: relative declines have not been

translated into absolute global reductions; national achievements may mean little in a global economy; and all of these reductive trajectories have their natural limits.

Even as relative ratings or performances improve, absolute totals of energy and materials used worldwide have been increasing, both because of continued population gains and because of higher levels of per capita consumption (larger houses, heavier cars, more common travel, more frequently updated electronic devices). Moreover, declining national rates of material and energy intensity are a misleading metric in a global economy in which deindustrialization of high-income countries (reducing or completely abandoning highly material- and energy-intensive industries) and reliance on imports make the global accounts the only relevant perspectives. And while in some cases there is plenty of room for further improvements, in other instances we have come close to the possible material minima, conversion maxima, or stoichiometric limits that will prevent further relative savings.

Prominent examples of energy efficiencies that are already close to their respective limits include such disparate converters as large electric motors and large wind turbines. Large electric motors have nominal efficiencies in excess of 90%. According to the Betz limit the top efficiency of wind turbines is 59.6% ([Betz 1926](#)), and today's best machines already perform at close to 80% of that maximum. The minimum energy to produce iron from ore is about 10.4 GJ/t; to synthesize ammonia from its elements is about 21 GJ/t—and today's best practices are, respectively, less than 20% and less than 30% above those levels ([Smil 2016a](#) and [2014](#)). But there can be no 100% efficient wind turbine (it would stop the wind) and no ammonia synthesized with less than the minimum heat of its formation: anything less than that would violate the laws of physics.

Some mass reductions have been similarly impressive. Between 1959 (the year of its commercial introduction) and 2011 the mass of a typical aluminum beverage can was reduced by 85%; it is now just above 10 g/can, and, obviously, it cannot go down to 1 or 2 mg. Turbofan engines powering the Boeing 787 in 2018 develop the same maximum thrust with 35% less material than those installed in Boeing 707 in 1958—and it is hard to think of a lighter material for the newest engine fan blades than carbon-fiber composite whose use has also allowed reducing the blade count from 22 to

18 ([GE Aviation 2019](#))—but there can be no turbofan with just a single blade.

The net outcome of this relative dematerialization has been an enormous increase in total demand for expensive, high-energy-intensity materials as the material gains were translated into rapidly increasing volume of travel. Planes are lighter, but pkms flown globally had increased about 40-fold between 1958 and 2018, multiply negating any relative dematerialization gains in constructing jetliners (mass/seat, mass/pkm). And this strong growth is expected to continue because air travel has not only been rising rapidly in all modernizing Asian countries but it has been also taking off in Africa: even in the poor sub-Saharan part of the continent the number of passengers had tripled since the year 2000 ([World Bank 2019](#)).

And this particular contrast between relative dematerialization and continued strong absolute growth of demand for high-quality materials is not an exception but just a specific illustration of a common reality. As already noted, this reality has brought large increases of aggregate and per capita material consumption on national and global scales, and reductions of relative material intensity will not be able to reduce the increased absolute demand for materials in modernizing countries of Africa and Asia, where most of the people will be born during the remainder of the 21st century and where they will hope to improve their quality of life, now comparable to levels achieved in affluent countries three to four generations ago! The conclusion is inescapable: there is no near-term prospect for any substantial absolute decline of material consumption in the global economy or for any major reduction of absolute energy inputs.

Largely ignoring, or insufficiently recognizing, the essential role of the biospheric goods and services in economic growth has been another common omission—and we do not even know how critical that role is, with the global estimates of aggregate value between \$33 and \$125 trillion ([WEF 2019](#); for comparison, in 2020 the global annual economic product was about \$90 trillion). None of this would make any difference if this omission were solely the matter of academic interest when debating the composition of growth models. My reaction to this way of treating the biosphere remains stubbornly grounded in evolution. While we might have set ourselves apart from other species, thanks to our large brains, and while our innovative drive has liberated us from many natural constraints, we remain carbon-

based organisms within the biosphere with all the limitations such reality implies ([Vernadskii 1926](#); [Smil 2002](#)).

Kenneth Boulding famously said that “anyone who believes in indefinite growth in anything physical, on a physically finite planet, is either mad or an economist” ([Boulding 1973](#), 248). He pioneered the distinction between the prevailing cowboy economy and the desirable spaceship (closed) economy, and pointed out, “In the cowboy economy, consumption is regarded as a good thing and production likewise. . . . By contrast, in the spaceman economy, throughput is by no means a desideratum, and is indeed to be regarded as something to be minimized rather than maximized” ([Boulding 1966](#), 7–8).

Nicholas Georgescu-Roegen ([1971](#), [1975](#)) and Herman Daly ([1971](#), [1980](#), [1996](#)) put economy on its rightful thermodynamic foundation, leading to Daly’s sarcastic remark that continuous economic growth on the Earth would be possible only if the economy were not a part of a non-growing biophysical system, if the growth would proceed solely in a nonphysical dimension, and, most importantly, if the laws of thermodynamics did not apply. Ecological approaches to economics received a wider attention during the 1970s, especially after the publication of *Limits to Growth*, a simplified (and in many ways misleading but highly influential) model of the planetary future based on Jay Forrester’s system dynamics (Meadows et al. 1971; [Forrester 1971](#)).

New support for ecological thinking came with the emergence of the notion of sustainable economy (WCED 1987); the International Society of Ecological Economics was founded in 1989 and concerns about the impacts of anthropogenic global warming helped to focus on alternative ways ahead, leading to many studies of not just reduced economic growth but of economies of deliberate decline ([Hardin 1992](#); [Daly 1996](#); [Coyle 2011](#); D’Alisa et al. 2014). But none of this has made any practical difference. Even the greatest post-WWII economic downturn turned out to be just a brief dip as the first two decades of the 21st century saw substantial growth of the global economic product (70% increase in constant monies), massive gains in energy supply (primary energy consumption up by about 48%; electricity generation up by 74%); and enormous increases in the use of materials (cement and aluminum output rising 2.6-fold and steel output more than doubling).

Sustainable growth and circular economy are fashionable phrases but the first notion has only tenuous links to reality of the early 21st century, and the second one is a biophysical impossibility. Any truly sustainable economy would have to run solely on renewable energies and have no material leakages. But modern economies rely on massive linear flows of energy and materials and waste large shares of mobilized resources. Only the abolishment of the laws of thermodynamics would make it possible to reuse the nearly 600 EJ of energy that are now consumed annually by modern civilization, with about 25% of that total embedded in the production of materials whose costs range from the lows of 3–4 GJ/t for cement to the highs of some 20 TJ/t for finished silicon wafers ([Smil 2014](#)).

Relatively high rates of recycling of some materials in some countries (aluminum in the United States, paper in Japan) are exceptions and even those often involve “down-cycling” (white printing paper becomes packaging cardboard), inevitable material losses, and often considerable energy costs. Other materials (above all many different kinds of plastics) are notoriously difficult to recycle. In any case, collection, separation, and reformation of discarded materials entails substantial additional energy inputs. For example, recycled glass (unlike aluminum) has only marginally lower energy cost than the primary product (no more than 10–15%) and this slight advantage disappears with rising collection and transportation costs. In addition, recycling has become more difficult, as previous processors of waste (most notably China) either banned or reduced their imports.

And there are no ways to recycle “hidden” material flows that accompany production of energy, metals, and nonmetallic minerals. These massive flows create environmental impacts but have no acknowledged economic value. They include overburden that must be removed prior to the extraction of minerals; processing wastes associated with the separation of metals from rocks (bauxite contains only 15–25% of aluminum, taconite has just 30–40% of iron, and cobalt ores contain just 1–2% of the element); soil, sand, and rocks displaced during construction projects; and soil eroded from fields. In aggregate, these hidden flows amount to more than half of globally displaced raw materials.

As for the food production, the most fundamental of all economic activities, there is absolutely no way that we could “circularize” the flows of key material inputs, water, fertilizers, and other agrochemicals. Reusing precipitation and irrigation water would require an unimaginable feat of

capturing all evapotranspiration and field runoff, as well as returning all water that is incorporated in harvested plants. And as already noted, global losses of applied fertilizer nitrogen (due to the combination of erosion, leaching, volatilization, and denitrification) average more than 50% of the nutrient's initial inputs. Given the extent of our wasteful uses, a constant quest for more efficient economic activities (be it in terms of energy, mass, or residual output) must be encouraged but any claims that we could create a truly circular economy are delusional.

A high degree of global economic integration is yet another, now deeply embedded, economic reality that works against reducing energy and material inputs. Affordable intercontinental shipping (the result of inexpensive fuel, efficient engines, and massively sized vessels) reduced, even eliminated, distance as a limiting factor. This integration has been true both in terms of basic commodities and manufactured products. Commodity trade relies on large bulk carriers for grain, cement, and ores and on tankers for liquid and gaseous fuels, while finished goods are transported in container ships and (more often than most people realize) by freighter aircraft. The latest Boeing airplane is a perfect example of a far-flung manufacturing network relying on such shipments.

Even noting just the major parts of the Boeing 787 reveals that the engines come either from the United States or the United Kingdom; the rear fuselage and tail fin are US-made; the central fuselage is shipped from Italy's Alenia, wings and their trailing edges from Japan (Mitsubishi and Kawasaki), landing-gear structures and passenger entry doors from France (Messier-Dowty and Latecoere), body fairings from Canada, wingtips from South Korea, and cargo access doors from Sweden ([Hale 2006](#)). Planes are then assembled in Washington and South Carolina—but it is now unimaginable that those giant assembly factories could source all parts from nearby suppliers and eliminate the cost of shipping. Because of these ubiquitous, embedded supply webs, we now operate globally more than 50,000 large ocean-going ships and thousands of cargo airplanes (and every intercontinental passenger flight also carries cargo), and rely on containerized railroad shipping and fleets of trucks, all being major, incessant consumers of energy and materials.

In addition, rising incomes lead to consumption of more expensive and hence often also more material- and energy-intensive goods (custom-built houses, luxury cars) and experiences (short car trips to a nearby lake or

mountains vs. intercontinental flights). Chinese experiences show how rapidly such demand can arise: in the year 2000 only one out of 200 Chinese urban households had a car, now four out of ten have it, and the total number of tourists traveling abroad had more than tripled during the ten years preceding 2018 (NBSC 2020). And the world now contains more than two billion people whose income level is where the Chinese mean was at the beginning of the country's economic modernization, a comparison indicating the enormous pent-up potential demand for these kinds of energetically and materially intensive consumption.

What Can Be Done?

Modern societies have a food supply that supports normal development in childhood and adolescence and that enables active life in adulthood; their access to health care prevents premature mortality and helps to lengthen active life span; education is available beyond the basic schooling; and average incomes allow for at least a modicum of material comforts, above all for decent housing. All of these requirements have been always predicated on sufficient flows of energies and materials, and their provision has become more challenging with the scale of demand and its future likely growth.

Abundant energies and materials are already available to about 1.5 billion people (about 20% of the global population) in affluent societies and among the upper income levels of modernizing economies. Almost the same number of people now live in societies (better-off strata in what the World Bank calls middle-income economies) in which such a combination of existential desiderata is clearly within sight, to be achieved perhaps in less than a generation. But the remainder of humanity—about 60%, or some 4.5 billion people—still live in societies in which those inputs remain far below the minima compatible with decent life. Reducing this inequality should be the greatest moral imperative for a global civilization, and no real progress toward that goal could be achieved without substantially higher energy and material inputs. That, of course, would make the decarbonization of the global energy supply and a reduction of CO₂ emissions even more challenging.

Since 1980 many nations in Asia, the Middle East, and Latin America have tripled or quadrupled their per capita use of materials (and China has seen a number of order-of-magnitude increases) and energy demand has seen similar, or even higher, increases in much of Asia. Africa, however, is still in the earliest stage of real consumption takeoff. Recent growth has been low in the two largest economies, Nigeria and South Africa, but encouraging trends are seen in Ethiopia, Ghana, and Tanzania ([World Bank 2019](#)). As their development advances they will need to multiply their per capita use of steel and cement to build their essential infrastructures and better urban housing.

Three key examples illustrate the magnitude of required transitions. If Africa were to replicate China's post-1980 rise of per capita energy use, then its today's consumption of fuels and electricity that would have to go up roughly tenfold, and if it were to match China's per capita steel consumption, then its annual production of the metal would have to increase more than 50-fold. And if sub-Saharan Africa were merely to match India's current level of nitrogen use in cropping, its demand for synthetic fertilizer would go up by an order of magnitude. Obviously, similarly stunning comparisons could be cited for aluminum, glass, plastics, or microprocessors.

Another way to illustrate this challenge in economic terms is to note that because of a skewed distribution of economic activities, about 70% of the world's population (including all of Africa and most of Asia) are now living in countries whose average per capita GDP is below the recent global mean. Lifting more than five billion people just to the mean of the global affluence would require increases of energy and material consumption at least twice as large as has been consumed by China's post-1980 economic rise. And replicating just the European Union's average of primary energy and material use (the US mean is more than twice as high) would mean that the poorest fifth of humanity would have to increase its consumption roughly tenfold.

But many *nouveaux riches* in Asia now aspire to go much beyond those moderately affluent EU averages and replicate the consumption now enjoyed by America's upper middle class, the richest fifth of the country's population ([Reeves 2017](#)). This affluent cohort now consumes annually more than 500 GJ of primary energy per capita a year, while humanity's poorest fifth has to make do with less than 20 GJ/capita. This is more than a

25-fold gap that could not be closed during the 21st century but that will, in the world with globally shared information, motivate the aspiration of millions in Asia, Africa, and Latin America.

Could we see the economic rise of low-income countries taking place without any further substantial impact on the global environment because of the reduced demand in high-income countries? True, all affluent, aging societies, often with shrinking populations, have seen mixtures of stagnant and declining per capita consumption rates for the past three to four decades. Even the US per capita primary energy demand (notwithstanding all the SUVs, larger houses, more mobility, and a surfeit of electronic gadgets) has not shown any upward trend: it has fluctuated between 280 and 300 GJ/year, while the European rates have been moving within a narrow range mostly between 140 and 170 GJ/year. But in either case the absolute post-1980 demand has risen, by about 25% in the United States and by 15% in the European Union.

Similarly, American and European per capita demand for key materials (metals, cement, paper, glass) has become either largely saturated or it has been declining. Absolute demand has seen much smaller shifts; for example, total US steel consumption declined by just 10% between 1980 and 2018—but that is no indicator of a great achievement: in order to fix and to update the country's failing infrastructure, the US steel consumption should be rising! Moreover, many materials displacing traditional choices have higher overall energy and environmental costs. Substitution of wood by plastics has been the most obvious example of such undesirable consequences. The energy cost of wood is generally less than 5 GJ/t; the energy cost of plastics is typically more than 100 GJ/t. And while discarded wooden objects decay naturally, plastic wastes persist. By 2014 there were more than five trillion plastic pieces afloat in the ocean ([Eriksen et al. 2014](#)) and plastic waste now reaches even the deepest ocean trenches ([Jamieson et al. 2019](#)).

And to bring a decent quality of life to all humanity while remaining within the recent rates of global energy and material use (and hence without further increasing any critical environmental impacts) would be impossible even if 1.5 billion people who enjoy a high standard of living were to cut their energy and material use by half and if those savings would then become fully available for consumption in low-income countries. In energy terms that would mean lowering the annual rate from the current mean of

about 180 GJ/capita to 90 GJ/capita: that is, no higher than China's recent average. (And, of course, in the US case, reducing average energy use to 90 GJ/capita would require cutting the consumption by two-thirds.) But even that enormous transfer of energy would leave today's low-income countries with per capita use well below the Chinese mean, and their populations will grow by some two billion by the mid-century.

If this option of the rich world's voluntary pauperization (still inadequate to bring about the desired change!) should be excluded as being completely unrealistic, then the same must be said about the possibility of providing all of those additional inputs by relaying solely on non-carbon energies and on materials produced without any fossil carbon input by relying on currently commercialized techniques and conversions. As I explained, there is no realistic way to eliminate our reliance on fossil carbon in a matter of a few decades while also relying on non-carbon energies to supply all additional requirements to modernize today's low-income societies. How difficult it would be to achieve any absolute reductions of near-term energy is illustrated by the admission in the final text of the Paris agreement. Even if all of the intended nationally determined contributions were met, the greenhouse gas emissions would "not fall within least-cost 20C scenarios but rather lead to a projected level of 55 gigatonnes in 2030" ([UN 2015](#), 4), the latter total being nearly 50% above the 2018 level!

But in order to avoid greater environmental consequences associated with 2°C warming, the average increase of the tropospheric temperature should be kept to less than 1.5°C ([IPCC 2018](#))—but the only way to achieve that would be to undergo an extraordinary shift away from fossil fuels to non-carbon substitutes. After growing steadily for more than 200 years—with another record (at 33.1 Gt CO₂) set in 2018 ([IEA 2019](#))—global CO₂ emission from fossil fuels would have to stop growing and start falling rapidly (by at least 1 Gt CO₂/year) in 2020 in order to be eliminated by 2050. Afterwards they would have to remain negative for the rest of the century, ending the 21st century 10–20% lower by 2100 than they were in 2018 ([IPCC 2018](#)).

The latter goal would need the removal of hundreds of billions of metric tons of CO₂ from the atmosphere and permanent underground sequestration of the gas: such scenarios are easy to produce by computer models primed by unrealistic assumptions. But realities will be very different and miraculous transformation would not be an exaggerated term if such

scenarios were to become a global reality. For techno-optimists none of the preceding is much of a concern: they believe that any requisite solutions will come from riding the endless escalator of scientific, technical, and managerial innovations in general and advances in electronics and artificial intelligence in particular, a shift that is now also called, modestly, [the Fourth Industrial Revolution \(Schwab 2016\)](#). But techno-optimist hopes are quaintly conservative compared to the promises the true believers make on behalf of the approaching singularity with its infinite eruption of electronic sapience in finite time.

But these are products of wishful thinking. As I demonstrated, the steady flow of innovations cannot prevent further increases in global demand. Even after reducing of today's food waste by a third, by 2050 the global population would require at least 20% more food just to maintain the current level of supply, and at least a third more in order to eliminate the existing undernourishment. Even if improvements in energy conversion efficiency run considerably above the historic rate, the world in 2050 would need at least a 40% higher supply of primary energy than in 2020, and an even higher increase in electricity generation. Even if relative dematerialization will progress, the total need for basic metals and nonmetallic minerals will expand significantly—and none of these food, energy, and material gains could be attained by eliminating all new fossil fuel uses.

As a result, the most likely course of the global development will not follow any of the four commonly expected trajectories. There will be declines but no radically reduced consumption in affluent countries. There will not be any rapid decarbonization, because current commercial capabilities limit that option. And effective solutions will not arrive either through the cumulative effect of new fundamental innovations or an early arrival of singularity. The best near-term outlook is for an early stabilization of releases followed by slow gradual decline. This approach not only could prevent further emission increases but it could also result in substantial declines below the current record levels. In contrast, only a worldwide economic retreat and condemnation of billions of people to lives of continuing misery could bring the end of emissions by 2050.

The global nature of CO₂ emissions and their consequences is poorly suited to adopting any resolute, binding national commitments that might yield the desired aggregate outcome. [Georgescu-Roegen \(1986, 18\)](#)

described the challenge in his retrospective examination of entropy law and economic growth by an observation of fundamental importance: “To economize energy . . . is not a task for one nation or even some nations. The task requires the cooperation of all nations, a point which reveals that there is a far more dreadful crisis than that of energy, namely, the crisis of the wisdom of homo sapiens sapiens.” Dealing with global climate change requires concerted global action, the shared adherence to well-defined long-term commitments.

But such commitments encounter very powerful forces, the universal human habit of profoundly discounting the future, even when making major decisions, and even when what is at stake is unprecedented—and especially when the time span involved is measured in decades rather than in years. In addition, it is naive to expect that scores of today’s dysfunctional states (unable to provide, despite their often considerable natural riches, a decent quality of life to their own citizens) will suddenly become effective partners contributing to the salvation of the global commons. Affluent countries should be capable of effective concerted action, but they would have to commit to a strategy of moderation and deliberate decline, promises that have yet to win any election.

Not surprisingly, remedies that have been favored to deal with the challenge have been both unoriginal and inadequate. Neither any contemplated levels of carbon taxes nor the subsidies for the adoption of non-carbon energy conversions will be able to reduce the emissions at the desired rate. Recall that such measures take place in the world where some 60% of its inhabitants deserve much higher consumption of energy and materials, and where, regardless of any subsidies, available non-carbon alternatives are not able to provide rapid solutions at requisite scales.

None of these realities are arguments for joining the recent apocalyptic chorus and its promises of rapidly approaching (or already nearly reached) tipping points and played-out humanity, nearly imminent collapse of Western and global civilization, and uninhabitable Earth ([Oreskes and Conway 2014](#); [Wallace-Wells 2019](#); [McKibben 2019](#); [Spratt and Dunlop 2019](#); [Lenton et al. 2019](#)). These visions present concatenations of the worst-case scenarios (relying by inherently uncertain models) as the most likely descriptions of unknown realities, and they also underestimate our ability (belated as it might be) to respond and to adapt. Apocalyptic claims are always counterproductive: religions have failed, for millennia, in using

them to threaten the faithful with horrific punishments in hell in order to convert humanity to angelic behavior.

Recent apocalyptic writings would not (if they were aware of them) convince Indian coal miners to quit their jobs and Indian planners to plunge the country into darkness (India generates 80% of its electricity from coal, with plans for further substantial expansion); they would not stop the Chinese farmers from using coal- and natural-gas-based nitrogenous fertilizers needed to double-crop their rice (they apply more nitrogen per hectare than any other staple grain growers) in order to feed the world's largest population by cultivating less land per capita than in Bangladesh. At the same time, the need for continuous quest for higher efficiencies, reduced waste, optimized design, more realistic pricing, effective taxation, helpful subsidies, and the ethos of moderate consumption are more urgent than ever.

All of these goals should be pursued with unprecedented intensity, and aggregate savings resulting from these measures could be quite significant. Do your own calculations to see how much carbon we would have prevented from reaching the atmosphere during the past generation if we had adopted stringent building codes and superinsulated our buildings, or if we had discouraged the mass ownership of heavy SUVs (better yet, if we had never introduced these bulked-up vehicles), or if we had priced air travel to reflect more closely its environmental impact. But we must be aware that even a determined quest for efficiency and rational consumption may not be enough to accomplish the transition toward a civilization able to live comfortably within additional impacts on the biosphere. And while the recent focus on climate change has sidelined concerns about many other environmental problems that degrade and pollute the biosphere, it must be stressed that many of these undesirable changes would not be resolved even by a miraculously instant cessation of greenhouse gas emissions.

Extraordinary challenges may call for extraordinary measures and that is why geoengineering—deliberate large-scale alteration of one or more processes affecting the Earth's climate—is seen by some as perhaps the best solution to the intractable global problem of reconciling carbon-based economic growth with the concerns about global climate change. Geoengineering proposals range from constant dispersal of aerosols (sulfates or carbonates) in the stratosphere to reduce the incoming radiation

and to cool the troposphere to changes of terrestrial albedo and mass-scale ocean fertilization ([Keith 2013](#); [Boyd and Vivian 2019](#)).

These options are theoretically promising, but practical complications range from the rights to manage global commons and asserting national sovereignty to unforeseen and unevenly distributed negative consequences of long-term radiation or albedo alterations. I agree with what one of today's keenest proponents of geoengineering wrote nearly a generation ago, that "we would be wise to begin with a renewed commitment to reduce our interference in natural systems rather than to act by balancing one interference with another" ([Keith 2000](#), 280).

Consequently, should the impacts of global warming unfold as recently predicted—including a further, and unevenly distributed, increase of the tropospheric temperature, a gradual ocean-level rise, and the continued retreat of mountain glaciers—then the most likely outcome during the coming decades will be a great deal of unavoidable economic, social, and environmental adaptation. Devoting resources to these efforts might be a more prudent course than putting faith in the inevitable success of exceptionally rapid and sufficiently transformative technical innovations that would suddenly bend the CO₂ emissions curve steeply downward and drive the annual increments below zero (implying mass-scale removal of the gas from atmosphere) by 2050.

Evolutionary evidence shows that we have been able to cope with change in its many guises, including climate change (the last glacial period followed by rapid deglaciation of northern continents). During the past century we had to overcome the destruction of two world wars (1914–1918, 1939–1945) and prolonged economic crisis (1929–1939) and accommodate the consequences of unprecedented population growth in order to reach new levels of global prosperity. We also coped with the annihilation threat of the Cold War (1945–1989) and had quickly adapted to steep increases of crude oil prices (1973–1980) while averting predicted famines and managing environmental threats ranging from acid rain (at one point considered the greatest peril to our ecosystems) to the destruction of the ozone layer.

Acting preemptively, with determination and collective foresight, might be preferable but historically we have rarely followed that course: breaking with the past and choosing new options is always easier to do under stress and during exceptional times. Adaptation efforts would be, of course, much easier in the affluent countries because their indicators of well-being

already show many unmistakable signs of saturation. Most of them—including adult body height, life expectancy, years of education, and per capita energy consumption—begin to saturate once per capita economic product has risen to around \$20,000, or once the average annual primary energy consumption has surpassed 100 GJ/capita.

And as low fertilities and aging populations have become the norm in nearly all affluent countries, it should not be that difficult to promote further declines in per capita use of energy and materials and to do so without any drastic reductions in the overall standard of living—as long as such efforts are accompanied by measures designed to reduce the extent of existing economic inequality. Adaptations in low-income countries would be much more difficult and even their partial success (diffusion of more suitable crops, improvements in water management, construction of appropriate housing, mass-scale adoption of new energy sources) would require considerable transfers of investment and expertise from affluent nations, or their increased willingness to accommodate substantial numbers of future migrants.

At the same time, we should never mistake our best indications of the future state of the global environment for highly reliable predictions of reality: many of our climate models are impressively more realistic than their predecessors were a generation or two ago (the origin of these models goes back to the late 1960s) but uncertainties are encountered in virtually every kind of long-term assessments of changes caused by the anthropogenic rise of atmospheric greenhouse gases. Those who study climate models in depth have no hesitation to acknowledge that the models remain uncertain “yet comparatively little effort is devoted to fixing it . . . and without such reductions in uncertainty, the science we do will not, by itself, be sufficient to provide robust information for governments, policy make and the public at large” ([Carslaw et al. 2018](#), 2).

Current models ignore solar activity (and its associated effects), do not adequately handle cloud microphysics, and cannot reproduce all hydrospheric and biospheric feedbacks that can affect future atmospheric CO₂, CH₄, and N₂O concentrations. As a result, we cannot be sure which conclusions based on the best current models may overestimate some specific consequences and which ones may underestimate long-term effects. A perfect example of this reality is provided by a study whose firm conclusions emerged only after 20 years of monitoring.

Higher concentrations of atmospheric CO₂ should, everything else being equal, promote terrestrial photosynthesis. This process has been verified many times in agricultural crops and in forests, and plants with the two principal metabolic pathways have different responses to elevated CO₂ concentrations. During the early period of the long-term CO₂ enrichment conducted by [Reich et al. \(2018\)](#), experimental plants behaved as expected, with C₃ species responding strongly to elevated CO₂ and C₄ plants being unresponsive. Gradually, the response of C₃ plants diminished while that of C₄ species strengthened, after 15–20 years C₄ species continued to respond strongly while the reaction of C₃ species was negligible, and during the final five years of the enrichment the response of C₄ plants exceeded that in C₃ plants at any stage of the experiment.

Because all major crops (except for corn, sorghum, and sugar cane) are C₃ and because the C₄ pathway of photosynthesis is absent among trees, these findings (contradicting the earlier consensus) have wide-ranging implications for our understanding of long-term response of plants to higher CO₂ levels. But several additional uncertainties are at play, as future plant responses will also depend on the amount and distribution of precipitation, availability of additional macro- and micronutrients, and the abundance of viral, fungal, and insect depredations. Response to droughts—as plants partially close their stomata in order to limit their evaporative water loss—may be particularly important because it also results in reduced carbon intake for photosynthesis. [Peters et al. \(2018\)](#) confirmed this trade-off over a period of ten years on ecosystem-wide scales over the Northern Hemisphere where severe droughts affected Europe, Russia, and the United States between 2001 and 2011.

They found the response to be substantially larger than simulated by six state-of-the-art climate models, suggesting that the modeled drought-induced carbon-climate feedbacks may be too small and that extensive and prolonged droughts can significantly affect the annual global carbon budget. And yet a recent report stated unequivocally that “China and India lead in greening the world through land-use management” as one-third of the world’s entire vegetated area is getting greener and only 5% is browning ([Chen et al. 2019](#), 486). That would be most welcome news, but reading beyond the headline reveals that the increasing leaf area of vegetation

recorded by satellites in those countries is largely due to the intensification of cropping. The combination of more widespread multicropping made possible by higher applications of fertilizers and by groundwater irrigation accounts for 82% of leaf area gains in India and 32% in China, where 42% has been due to the planting of trees, overwhelmingly monocultural fast-growing (and often non-native) species poorly adapted to their new environments and of questionable long-term benefits ([Xu 2011](#)).

Consequently, the reported greening (a desirable outcome) creates further undesirable environmental impacts and raises more concerns than approbation. And vegetation response is, as in so many other cases, dependent on a number of hard-to-predict developments. Uncertainties regarding the future changes associated with global warming extend to dozens of variables, ranging from the rate of melting of the Antarctic ice and its contribution to the rising sea level ([Rignot et al. 2018](#); [Schlegel et al. 2018](#)), and from the decline of dissolved oxygen in the ocean ([Schmidtko et al. 2017](#)) to the volume of CH₄ and CO₂ that could be released by the melting of permafrost and that could increase annual fluxes of these greenhouse gases and accelerate the progress of warming ([Schurr et al. 2015](#)).

Yet another major uncertainty concerns the eventual impact of methane released from the seafloor. Such releases could amplify global warming but [Pholman et al. \(2017\)](#) found that an Arctic site with a high methane flux had also significant CO₂ uptake whose effect overwhelmed the warming effect due to methane efflux. If this finding has a broader applicability then the area of methane seepage may be greenhouse gas sinks rather than sources!

And even if we knew what biophysical changes will actually take place by 2050 or 2075, we would remain on highly uncertain ground when trying to predict the responses (or lack of them) to these changes undertaken by individual countries. Past developments show that specific national responses to major challenges can lead to enormously different outcomes. As recently as 1990 Nigeria's per capita GDP was twice that of China, and today's Nigeria still has (in relative terms) more resources than China, and it still enjoys its demographic dividend—but during the past three decades its per capita GDP grew by just 50% while China's average rose tenfold!

All of these inescapable uncertainties make it imperative that we do not foreclose any potentially rewarding solutions by applying doctrinaire

selection of choices. This has been my key argument for decades. We should be

acting as complexifying minimalists rather than as simplifying maximalists, being determined but flexible, eclectic but discriminating. The first contrast means favoring a multitude of approaches rather than relying on any single (and purportedly perfect) solution and championing minimal inputs compatible with the highest achievable useful services. The other contrasts mean that there should be no place for a priori ideological purity that would not tolerate particular solutions, no categorical exclusions of certain ingredients . . . and no inflexible insistence on what is best” ([Smil 2003](#), 367).

In practice this plan means (to start with just a few energy examples) promoting systems designs (for example, not producing more efficient SUVs whose adoption has, so far, eliminated any benefits from the introduction of electric vehicles), avoiding picking a priori favorites (labeling nuclear electricity generation as unacceptable under any circumstances or extolling it as the solution), recognizing the advantages and drawbacks of photovoltaics (the highest power density among the renewable conversions vs. the need for large-scale electricity storage in any system with a high share of PV capacity), or not foreclosing the development of hydrogen-powered vehicles by overtly preferring the adoption of battery-powered cars by offering substantial rebates and imposing national ownership targets. In food production and nutrition this approach requires keeping species diversity, focusing on reducing waste at every level, adjusting intakes for seasonal differences (not every fruit has to be constantly available), recognizing the inherent limits of currently fashionable “urban agriculture” (without dismissing its potential for supplementary cultivation of some high-value crops), or stopping the use of crop-derived biofuels in monstrosly heavy vehicles.

Extreme scenarios are easy to outline. Either the equilibrium climate sensitivity (the average global warming resulting from the doubling of preindustrial CO₂ concentrations) will remain close to the bottom of the predicted range (making the consequences more bearable and the adaptation easier)—or it will go well past it into a perilous realm. Either we will find enough global commitment to stabilize the current level of carbon emissions prior to engineering their steady decline—or we will have no effective agreement and will have to live with even higher than anticipated levels. Either the complex natural responses to global warming (above all the storage in plants and in the ocean) will provide greater buffers than we

anticipate—or they will largely fail, leaving us with even more pronounced undesirable effects.

The most likely outcome will include an unpredictable mixture of components from the entire spectrum of possibilities. We do not know what lies ahead; even the best probabilistic assessments of specific outcomes are, despite their hedged nature, just matters of educated guesses. The notion that in 2020 we can anticipate the world of 2100 is utterly risible. Just look back to the world of 1940 and see what did not exist, and what was not anticipated, in that world. There were no antibiotics, no contraceptives, no nations with below-replacement fertility, no nationwide life expectancies above 60, and no countries where most adults were overweight or obese. When we move our focus from populations to agriculture and food, there were no herbicides, no high-yielding short-stalked cereals, no transgenic crops, no no-till cropping, no central animal feeding operations, no mass-scale greenhouses growing vegetables, no cultivation under plastic sheets, and (bananas aside) no intercontinental trade in fresh fruit.

When we turn to energy, there were no giant open-cast mines, no Saudi oilfields, no offshore drilling (out of the sight of land or in deep waters), no hydraulic fracturing, no liquefied natural gas, no giant oil or LNG tankers, no gigawatt-sized turbogenerators, no widely deployed gas turbines, no flue gas desulfurization, no nuclear reactors, no high-voltage direct-current lines, no PV cells, no wind turbines. Economies had to do without any computers, satellites, jetliners, container shipping, and rapid trains; there was no steel produced in basic oxygen furnaces, no plate glass made by floating on molten metal, no centrifugal compressors in ammonia synthesis, no composite materials, no solid-state electronic devices and hence no Internet, no mobile phones, no essentially instant and free flow of information. And there were no concerns about acid rain, ozone layer or greenhouse gases; there was no photochemical smog, no antibiotic resistance, no pesticide residues, no mass-scale plastic waste.

Contrary to many modeling dreams, the future remains unknowable, but we know that many options remain available, that choices of possible trajectories and effective alternatives have not been irrevocably foreclosed by our past actions. Grand transitions of population and economic growth, of energy use, and of environmental impacts have brought us to this point in human evolution when both promises and perils have reached their respective extremes exemplified by the claims of approaching singularity

and equidistant apocalypse: both are “scheduled” by their proponents to take place before 2050, perhaps even by 2030. I do not believe that in such a short time we will face either an apocalyptic outcome or a care-free singularitarian future of boundless intelligence.

The chances are that we will continue to deal with the coming transition to a civilization operating within the biospheric limits with a combination of aggressive inventiveness and inexplicable procrastination, of effective adaptability and infuriating failure to respond. Will we succeed? The answer hinges on the definition of success, but once all the gains and losses have been factored in, it would be surprising if transitions likely to be accomplished during the 21st century were less transformative than those experienced during the 20th century. Another epochal transition is unfolding and its outcome is not foreordained; it remains contingent on our choices. In that sense, at least, *nihil novi sub sole* . . .

APPENDIX

Scientific Units and Their Multiples and Submultiples

Basic International System of Units (SI) used in the text

Quantity	Name	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s

Other units used in the text

Quantity	Name	Symbol
Area	hectare	ha
	square meter	m ²
Energy	joule	J
Mass	gram	g
	metric ton	t
Power	watt	W
Temperature	degree celsius	°C
Volume	cubic meter	m ³

Multiples in the SI units used in the text

Prefix	Abbreviation	Scientific notation
Hecto	h	10^2
Kilo	k	10^3
Mega	M	10^6
Giga	G	10^9
Tera	T	10^{12}
Peta	P	10^{15}
Exa	E	10^{18}
Zetta	Z	10^{21}
Yotta	Y	10^{24}

Submultiples used in the International System of Units

Prefix	Abbreviation	Scientific notation
Deci	d	10^{-1}
Centi	c	10^{-2}
Milli	m	10^{-3}
Micro	μ	10^{-6}
Nano	n	10^{-9}

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