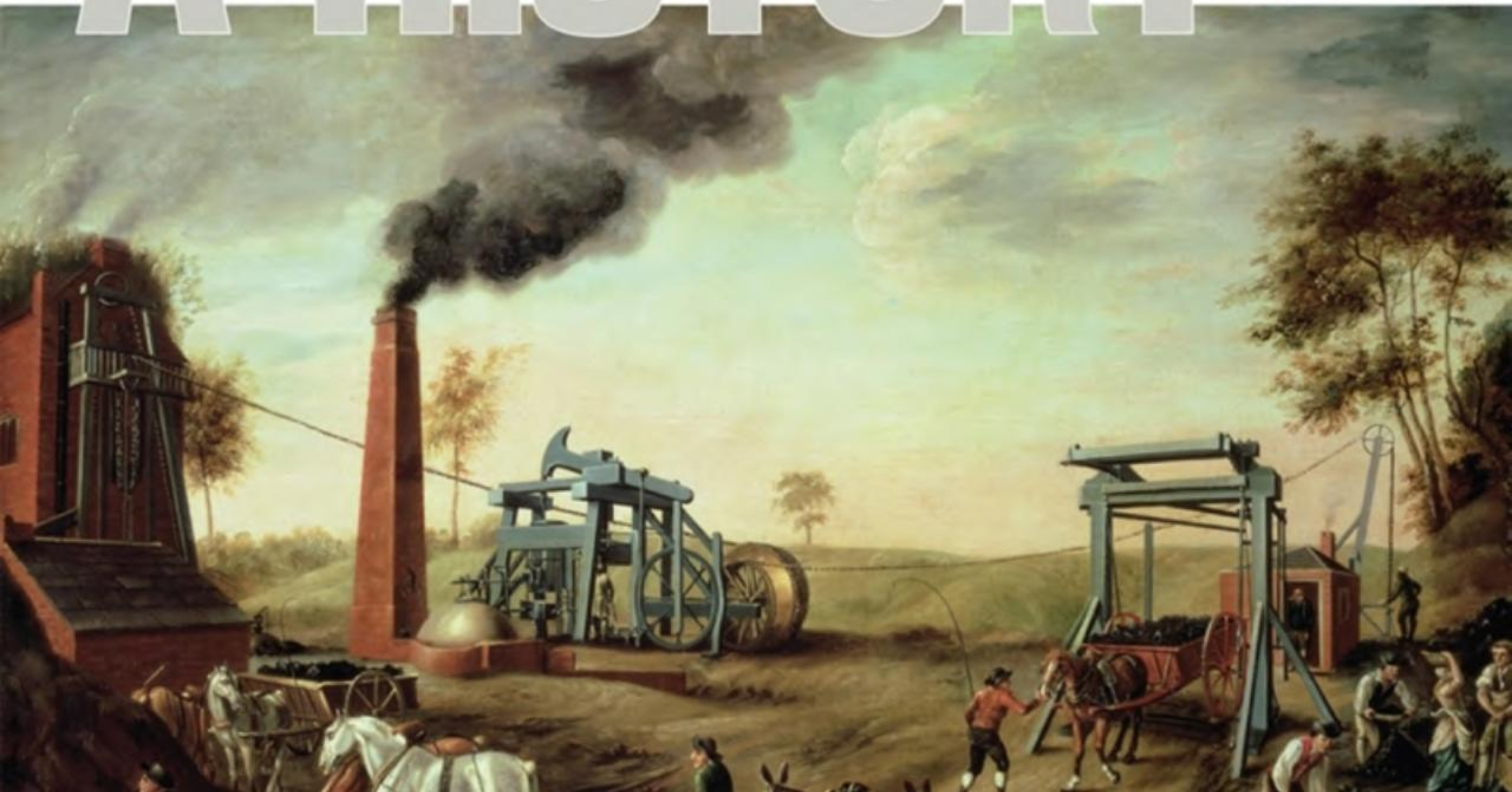
ENERGY AND CIVILIZATION
A HISTORY



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Preface and Acknowledgments

I finished writing *Energy in World History* in July 1993; the book came out in 1994, and it remained in print for two decades. Since 1994 energy studies have been through a period of great expansion, and I have added to it by publishing nine books dealing explicitly with energy matters and a dozen interdisciplinary books with significant energy components. Consequently, once I decided to revisit this fascinating topic it was obvious that superficial updating would not do. As a result, this is a substantially new book with a new title: the text is nearly 60% longer than the original, and there are 40% more images and more than twice as many references. Boxes sprinkled throughout the book contain some surprising calculations, as well as many detailed explanations of important topics and essential tables. I have also quoted from sources ranging from the Classics—Apuleius, Lucretius, Plutarch—to nineteenth- and twentieth-century observers such as Braudel, Eden, Orwell, and Senancour. Graphics were updated and created by Bounce Design in Winnipeg; two dozen archival photographs were secured from Corbis in Seattle by Ian Saunders and Anu Horsman. As is always the case with interdisciplinary studies of this kind, this book would not have been possible without the work of hundreds of historians, scientists, engineers, and economists.

Winnipeg, August 2016

But restating that fundamental link (as Orwell did) and claiming that cultural refinements have taken place with every refinement of energy flux (as Fox does) are two different things. Orwell's conclusion is unexceptionable. Fox's phrasing is clearly a restatement of a deterministic view expressed two generations earlier by the anthropologist Leslie White (1900–1975), who called it the first important law of cultural development: "Other things being equal, the degree of cultural development varies directly as the amount of energy per capita per year harnessed and put to work" (White 1943, 346). While there can be no dispute either about Ostwald's fundamental formulation or about energy's all-encompassing effect on the structure and dynamics of evolving societies (pace Orwell), a deterministic linking of the level of energy use with *cultural* achievements is a highly arguable proposition. I examine that causality (or the lack of it) in the book's closing chapter.

The fundamental nature of the concept is not in doubt. As Robert Lindsay (1975, 2) put it,

> If we can find a single word to represent an idea which applies to every element in our existence in a way that makes us feel we have a genuine grasp of it, we have achieved something economical and powerful. This is what has happened with the idea expressed by the word energy. No other concept has so unified our understanding of experience.

But what is energy? Surprisingly, even Nobel Prize winners have great difficulty in giving a satisfactory answer to that seemingly simple question. In his famous *Lectures on Physics,* Richard Feynman (1918–1988) stressed that "it is important to realize that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in little blobs of a definite amount" (Feynman 1988, 4–2).

What we do know is that all matter is energy at rest, that energy manifests itself in a multitude of ways, and that these distinct energy forms are linked by numerous conversions, many of them universal, ubiquitous, and incessant, others highly localized, infrequent, and ephemeral (fig. 1.1). The understanding of these stores, potentials, and transformations was rapidly expanded and systematized mostly during the nineteenth century, and this knowledge was perfected during the twentieth century when—a telling comment on the complexities of energy transformations—we understood how to release nuclear energy sooner (theoretically by the late 1930s, practically by 1943, when the first reactor began to operate) than we knew how photosynthesis works (its sequences were unraveled only during the 1950s).

Matrix of energy conversions. Where more possibilities exist, no more than two leading transformations are identified.

Flows, Stores, and Controls

All known forms of energy are critical for human existence, a reality precluding any rank ordering of their importance. Much in the course of history has been determined and circumscribed by both universal and planetary flows of energy and by their regional or local manifestations. The fundamental features of the universe are governed by gravitational energy, which orders countless galaxies and star systems. Gravity also keeps our planet orbiting at just the right distance from the Sun, and it holds a sufficiently massive atmosphere that makes Earth habitable (box 1.1).

As with all active stars, fusion powers the Sun, and the product of those thermonuclear reactions reaches Earth as electromagnetic (solar, radiant) energy. Its flux ranges over a broad spectrum of wavelengths, including visible light. About 30% of this enormous flow is reflected by clouds and surfaces, about 20% is absorbed by the atmosphere and clouds, and the remainder, roughly half of the total inflow, is absorbed by oceans and

Box 1.1

Gravity and the habitability of Earth

Extreme tolerances of carbon-based metabolism are determined by the freezing point of water, whose liquid form is required for the formation and reactions of organic molecules (the lower bound), and by temperatures and pressures that destabilize amino acids and break down proteins (the upper bound). Earth's continuously habitable zone—the range of orbital radius ensuring optimal conditions for a life-supporting planet—is very narrow (Perkins 2013). A recent calculation concluded that we are even closer to the limit than previously thought: Kopparapu and co-workers (2014) concluded that, given its atmospheric composition and pressure, Earth orbits at the inner edge of the habitable zone, just outside the radius where the runaway greenhouse effect would bring intolerably high temperatures.

About two billion years ago enough carbon dioxide (CO_2) was sequestered by the ocean and by archaea and algae to prevent this effect on Earth, but if the planet had been a mere 1% farther from the Sun, virtually all of its water would have been locked in glaciers. And even with temperatures within an optimum band the planet could not support highly diversified life without its unique atmosphere, dominated by nitrogen, enriched by oxygen from photosynthesis, and containing a number of important trace gases regulating surface temperature—but this thin gaseous envelope could not persist without the planet being sufficiently large to exert enough gravity to hold the atmosphere in place.

continents, gets converted to thermal energy, and is reradiated into space (Smil 2008a). The geothermal energy of Earth adds up to a much smaller heat flux: it results from the original gravitational accretion of the planetary mass and from the decay of radioactive matter, and it drives grand tectonic processes, which keep reordering oceans and continents and cause volcanic eruptions and earthquakes.

Only a tiny part of the incoming radiant energy, less than 0.05%, is transformed by photosynthesis into new stores of chemical energy in plants, providing the irreplaceable foundation for all higher life. Animate metabolism reorganizes nutrients into growing tissues and maintains bodily functions and constant temperature in all higher species. Digestion also generates the mechanical (kinetic) energy of working muscles. In their energy conversions, animals are inherently limited by the size of their bodies and by the availability of accessible nutrition. A fundamental distinguishing characteristic of our species has been the extension of these physical limits through a more efficient use of muscles and through the harnessing of energies outside our own bodies.

Unlocked by human intellect, these extrasomatic energies have been used for a growing variety of tasks, both as more powerful prime movers and as fuels whose combustion releases heat. The triggers of energy supplies depend on the flow of information and on an enormous variety of artifacts. These devices have ranged from such simple tools as hammerstones and levers to complex fuel-burning engines and reactors releasing the energy of nuclear fission. The basic evolutionary and historical sequence of these advances is easy to outline in broad qualitative terms. As with any nonphotosynthesizing organism, the most fundamental human energy need is for food. Foraging and scavenging by hominins were very similar to the food acquisition practices of their primate ancestors. Although some primates—as well as a few other mammals (including otters and elephants), some birds (ravens and parrots), and even some invertebrates (cephalopods)—have evolved a small repertory of rudimentary tool-using capabilities (Hansell 2005; Sanz, Call, and Boesch 2014; fig. 1.2), only hominins made toolmaking a distinguishing mark of their behavior.

Chimpanzee (*Pan troglodytes*) in Gabon using tools to crack nuts (Corbis).

Tools have given us a mechanical advantage in the acquisition of food, shelter, and clothing. The mastery of fire greatly extended our range of habitation and set us further apart from animals. New tools led to the harnessing of domesticated animals, the building of more complex muscle-powered machines, and the conversion of a tiny fraction of the kinetic energies of wind and water to useful power. These new prime movers multiplied the power under human command, but for a very long time their use was circumscribed by the nature and magnitude of the captured flows. Most obviously, this was the case with sails, ancient and effective tools whose capabilities were restricted for millennia by prevailing wind flows and persistent ocean currents. These grand flows steered the late fifteenth-century European transatlantic voyages to the Caribbean. They also prevented the Spaniards from discovering Hawaii, even though Spanish trading ships, the Manila Galleons (Galeón de Manila), sailed once or twice a year across the Pacific from Mexico (Acapulco) to the Philippines for 250 years between 1565 and 1815 (Schurz 1939).

Controlled combustion in fireplaces, stoves, and furnaces turned the chemical energy of plants into thermal energy. This heat has been used directly in households and in smelting metals, firing bricks, and processing and finishing countless products. The combustion of fossil fuels made all of these traditional direct uses of heat more widespread and more efficient. A number of fundamental inventions made it possible to convert thermal energy from the burning of fossil fuels to mechanical energy. This was done first in steam and internal combustion engines, then in gas turbines and rockets. We have been generating electricity by burning fossil fuels, as well by harnessing the kinetic energy of water, since 1882, and by fissioning a uranium isotope since 1956.

The combustion of fossil fuels and the generation of electricity created a new form of high-energy civilization whose expansion has now encompassed the whole planet and whose primary energy sources now include small but rapidly rising shares of new renewable sources, especially solar (harnessed by photovoltaic devices or in concentrating solar power plants) and wind (converted by large wind turbines). In turn, these advances have been predicated on a concatenation of other developments. To use a flow-model analogy, a combination of gates (valves) had to be set up and activated in proper sequence to enable the flow of human ingenuity.

The most notable gates required to release great energy potentials include requisite educational opportunities, predictable legal arrangements, transparent economic rules, the adequate availability of capital, and conditions conducive to basic research. Not surprisingly, it usually takes generations to

Box 1.3
Measuring energy and power

The official definition of a joule is the work accomplished when a force of one newton acts over a distance of one meter. Another option is to define a basic energy unit through heat requirements. One calorie is the amount of heat needed to raise the temperature of 1 cm^3 of water by 1°C. That is a tiny amount of energy: to do the same for 1 kg of water calls for a thousand times more energy, or one kilocalorie (for the complete list of multiplier prefixes, see "Basic Measures" in the Addenda). Given the equivalence of heat and work, all that is required to convert calories to joules is to remember that one calorie equals roughly 4.2 joules. The conversion is equally simple for the still common nonmetric English measure, the British thermal unit. One Btu contains roughly 1,000 J (1,055, to be exact). A good comparative yardstick is the average daily food need. For most moderately active adults it is 2–2.7 Mcal, or about 8–11 MJ, and 10 MJ could be supplied by eating 1 kg of whole wheat bread.

In 1782 James Watt calculated in his *Blotting and Calculation Book* that a mill horse works at a rate of 32,400 foot-pounds a minute—and the next year he rounded this to 33,000 foot-pounds (Dickinson 1939). He assumed an average walking speed of about 3 feet per second, but we do not know where he got his figure for an average pull of about 180 pounds. Some large animals were that powerful, but most horses in eighteenth-century Europe could not sustain the rate of one horsepower. Today's standard unit of power, one watt, is equal to the flow of one joule per second. One horsepower is equal to about 750 watts (745.699, to be exact). Consuming 8 MJ of food a day corresponds to a power rate of 90 W (8 MJ/24 h × 3,600 s), less than the rating of a standard light bulb (100 W). A double toaster needs 1,000 W, or 1 kW; small cars deliver around 50 kW; a large coal-fired or nuclear power plant produces electricity at the rate of 2 GW.

88%) water, with less than 10% carbohydrates, 2% protein, and 0.5% lipids, and has an energy density of just 1.7 MJ/kg (Feugang et al. 2006). This means that even a small woman surviving only on the carbohydrates of cactus pears (assuming, unrealistically, virtually no need for the other two macronutrients) would have to eat 5 kg of the fruit every day—but she could get the same amount of energy from only about 650 g of ground corn consumed as tortillas or tamales.

Power density is the rate at which energies are produced or consumed per unit of area and hence is a critical structural determinant of energy

Two horses turning a capstan geared to pumping well water in a mid-eighteenth-century French carpet manufactory (reproduced from the *Encyclopédie* [Diderot and d'Alembert 1769–1772]). An average horse of that period could not sustain a steady work rate of one horsepower. James Watt used an exaggerated rating to ensure customers' satisfaction with his horsepower-denominated steam engines installed to place harnessed animals.

Box 1.4

Energy densities of foodstuffs and fuels

Ranking	Examples	Energy density (MJ/kg)
Foodstuffs		
Very low	Vegetables, fruits	0.8–2.5
Low	Tubers, milk	2.5–5.0
Medium	Meats	5.0–12.0
High	Cereal and legume grains	12.0–15.0
Very high	Oils, animal fats	25.0–35.0
Fuels		
Very low	Peats, green wood, grasses	5.0–10.0
Low	Crop residues, air-dried wood	12.0–15.0
Medium	Dry wood	17.0–21.0
	Bituminous coals	18.0–25.0
High	Charcoal, anthracite	28.0–32.0
Very high	Crude oils	40.0–44.0

Sources: Specific energy densities for individual foodstuffs and fuels are listed in Merrill and Watt (1973), Jenkins (1993), and USDA (2011).

systems (Smil 2015b). For example, city size in all traditional societies depended on fuelwood and charcoal, and it was clearly limited by the inherently low power density of phytomass production (box 1.5, fig. 1.4). The power density of sustainable annual tree growth in temperate climates is at best equal to 2% of the power density of energy consumption for traditional urban heating, cooking, and manufactures. Consequently, cities had to draw on nearby areas at least 30 times their size for fuel supply. This reality restricted their growth even where other resources, such as food and water, were adequate.

Yet another rate, one that has assumed great importance with advancing industrialization, is the ***efficiency of energy conversions***. This ratio of output/input describes the performance of energy converters, be they stoves, engines, or lights. While we cannot do anything about the entropic dissipation, we can improve the efficiency of conversions by lowering the amount of energy required to perform specific tasks (box 1.6). There are fundamental (thermodynamic, mechanical) constraints to these improvements, but we have pushed some processes close to the practical efficiency limits,

Box 1.5

Power densities of phytomass fuels

Photosynthesis converts less than 0.5% of incoming solar radiation into new phytomass. The best annual fuelwood productivities of traditional fast-growing species (poplars, eucalyptus, pines) were no more than 10 t/ha, and in drier regions the rates were between 5 and 10 t/ha (Smil 2015b). With the energy density of dry wood averaging 18 GJ/t, the harvest of 10 t/ha would translate into a power density of about 0.6 W/m^2: (10 t/ha × 18 GJ)/3.15 × 107 (seconds in one year) = ~5,708 W; 5,708 W/10,000 m^2 (ha) = ~0.6 W/m^2. A large eighteenth-century city would have required at least 20–30 W/m^2 of its built-up area for heating, cooking, and artisanal manufactures, and its fuelwood would have had to come from an area at least 30 and up to 50 times its size.

But cities required plenty of charcoal, the only preindustrial smokeless fuel preferred for indoor heating by all traditional civilizations, and charcoaling entailed further substantial energy loss. Even by the mid-eighteenth century the typical charcoal-to-wood ratio was still as high as 1:5, which means that in energy terms (with dry wood at 18 GJ/t and charcoal [virtually pure carbon] at 29 GJ/t), this conversion was only about 30% efficient (5 × 18/29 = 0.32), and the power density of wood harvests destined for charcoal production was only about 0.2 W/m^2. Consequently, large preindustrial cities located in a northern temperate climate and relying heavily on charcoal (China's Xi'an or Beijing would be good examples) would have required a wooded area at least 100 times their size to ensure a continuous supply of that fuel.

Figure 1.4

Charcoaling in early seventeenth-century England as depicted in John Evelyn's *Silva* (1607).

Box 1.6

Efficiency improvements and the Jevons paradox

Technical advances have brought many impressive efficiency gains, and the history of lighting offers one of the best examples (Nordhaus 1998; Fouquet and Pearson 2006). Candles convert just 0.01% of chemical energy in tallow or wax to light. Edison's light bulbs of the 1880s were roughly ten times as efficient. By 1900, coal-fired electricity-generating plants had efficiencies of just 10%; light bulbs turned no more than 1% of electricity into light, and hence about 0.1% of coal's chemical energy appeared as light (Smil 2005). The best combined-cycle gas turbine plants (using hot gas exiting a gas turbine to produce steam for a steam turbine) are now about 60% efficient, while fluorescent lights have efficiencies up to 15%, as do light-emitting diodes (USDOE 2013). This means that about 9% of energy in natural gas ends up as light, a 90-fold gain since the late 1880s. Such gains have saved capital and operation costs and lowered environmental impacts.

But in the past, the rise of conversion efficiency did not necessarily result in actual energy savings. In 1865 Stanley Jevons (1835–1882), an English economist, pointed out that the adoption of more efficient steam engines was accompanied by large increases in coal consumption and concluded, "It is wholly a confusion of ideas to suppose that the economical use of fuels is equivalent to a diminished consumption. The very contrary is the truth. As a rule, new modes of economy will lead to an increase of consumption according to a principle recognized in many parallel instances" (Jevons 1865, 140). This reality has been confirmed by many studies (Herring 2004, 2006; Polimeni et al. 2008), but in affluent countries, those whose high per capita energy use has approached, or already reached, saturation levels, the effect has been getting weaker. As a result, rebounds attributable to higher efficiency at the end-use level are often small and decrease over time, and specific economy-wide rebounds may be trivial, and even net positive (Goldstein, Martinez, and Roy 2011).

though in most instances, including such common energy converters as internal combustion engines and lights, there is still much room for further improvement.

When efficiencies are calculated for the production of foodstuffs (energy in food/energy in inputs to grow it), fuels, or electricity they are usually called ***energy returns***. Net energy returns in every traditional agriculture relying solely on animate power had to be considerably greater than one: edible harvests had to contain more energy than the amount consumed as food and feed needed not only by people and animals producing those

Box 1.9

Energy returns on energy investment

Differences in the quality and accessibility of fossil fuels are enormous: thin underground seams of low-quality coal versus a thick layer of good bituminous coal that can be extracted in open-cast mines, or supergiant Middle Eastern hydrocarbons fields versus low-productivity wells that require constant pumping. As a result, specific EROEI values differ substantially—and they can change with the development of more efficient recovery techniques. The following ranges are only approximate indicators, illustrating differences among leading extraction and conversion methods (Smil 2008a; Murphy and Hall 2010). For coal production they range between 10 and 80, while for oil and gas they have ranged from 10 to far above 100; for large wind turbines in the windiest locations they may approach 20 but are mostly less than 10; for photovoltaic solar cells they are no higher than 2; and for modern biofuels (ethanol, biodiesel) they are at best only 1.5, but their production has often entailed an energy loss or no net again (an EROEI of just 0.9–1.0).

Complexities and Caveats

Using standard units to measure energy storages and flows is physically straightforward and scientifically impeccable—yet these reductions to a common denominator are also misleading. Above all, they cannot capture critical qualitative differences among various energies. Two kinds of coal may have an identical energy density, but one may burn very cleanly and leave behind only a small amount of ash, while the other may smoke heavily, emit a great deal of sulfur dioxide, and leave a large incombustible residue. An abundance of high-energy-density coal ideal for fueling steam engines (the often used adjective "smokeless" must be seen in relative terms) was clearly a major factor contributing to the British dominance of nineteenth-century maritime transport, as neither France nor Germany had large coal resources of comparable quality.

Abstract energy units cannot differentiate between edible and inedible biomass. Identical masses of wheat and dry wheat straw contain virtually the same amount of heat energy, but straw, composed mostly of cellulose, hemicellulose, and lignin, cannot be digested by humans, while wheat (comprised of about 70% complex starchy carbohydrates and up to 14% protein) is an excellent source of basic nutrients. They also hide the specific origin of food energy, a matter of great importance for proper nutrition.

Many high-energy foods contain no, or hardly any, protein and lipids, two nutrients required for normal body growth and maintenance, and they may not provide any essential micronutrients—vitamins and minerals.

There are other important qualities hidden by abstract measures. Access to energy stores is obviously a critical matter. Tree stem wood and branch wood have the same energy densities, but without good axes and saws, people in many preindustrial societies could only gather the latter fuel. That is still the norm in the poorest parts of Africa or Asia, where children and women gather woody phytomass; and its form, and hence its transportability, also matters because they have to carry wood (branch) loads home on their heads, often for considerable distances. Ease of use and conversion efficiency can be decisive in choosing a fuel. A house can be heated by wood, coal, fuel oil, or natural gas, but the best gas furnaces are now up to 97% efficient, hence far cheaper to operate than any other option.

Burning straw in simple stoves requires frequent stoking, while large wood pieces can be left burning unattended for hours. Unvented (or poorly vented, through a hole in the ceiling) indoor cooking with dry dung produces much more smoke than the burning of seasoned wood in a good stove, and indoor biomass combustion remains a major source of respiratory illnesses in many low-income countries (McGranahan and Murray 2003; Barnes 2014). And unless their origins are specified, densities or energy flows do not differentiate between renewable and fossil energies—yet this distinction is fundamental to understanding the nature and durability of a given energy system. Modern civilization has been created by the massive, and increasing, combustion of fossil fuels, but this practice is clearly limited by their crustal abundance, as well as by the environmental consequences of burning coals and hydrocarbons, and high-energy societies can ensure their survival only by an eventual transition to nonfossil sources.

Further difficulties arise when comparing the efficiencies of animate and inanimate energy conversions. In the latter case it is simply a ratio of fuel or electricity inputs and useful energy output, but in the former case daily food (or feed) intake should not be counted as an energy input of human or animal labor because most of that energy is required for basal metabolism—that is, to support the functioning of the body's vital organs and to maintain steady body temperature—and basal metabolism operates regardless of whether people or animals rest or work. Calculating the net energy cost is perhaps the most satisfactory solution (box 1.10).

But even in much simpler societies than ours a great deal of labor was always mental rather than physical—deciding how to approach a task,

Box 1.10

Calculating the net energy cost of human labor

There is no universally accepted way to express the energy cost of human labor, and calculating the net energy cost is perhaps the best choice: it is a person's energy consumption above the existential need that would have to be satisfied even if no work were done. This approach debits human labor with its actual incremental energy cost. Total energy expenditure is a product of basal (or resting) metabolic rate and physical activity level (TEE = BMR × PAL), and the incremental energy cost will obviously be the difference between TEE and BMR. The BMR of an adult man weighing 70 kg would be about 7.5 MJ/d, and for a 60 kg woman it would be about 5.5 MJ/day. If we assume that hard work will raise the daily energy requirement by about 30%, then the net energy cost would be about 2.2 MJ/day for men and 1.7 MJ/day for women, and hence I will use 2 MJ/day in all approximate calculations of net daily energy expenditures in foraging, traditional farming, and industrial work.

Daily food intake should not be counted as an energy input of labor: basal metabolism (to support vital organs, circulate the blood, and maintain a steady body temperature) operates regardless of whether we rest or work. Studies of muscle physiology, especially the work of Archibald V. Hill (1886–1977, recipient of the Nobel Prize in Physiology in 1922), made it possible to quantify the efficiency of muscular work (Hill 1922; Whipp and Wasserman 1969). The net efficiency of steady aerobic performances is about 20%, and this means that 2 MJ/day of metabolic energy attributable to a physical task would produce useful work equal to about 400 kJ/day. I will use this approximation in all relevant calculations. In contrast, Kander, Malanima, and Warde (2013) used total food intake rather than actual useful energy expenditure in their historical comparison of energy sources. They assumed an average annual food intake of 3.9 GJ/capita, unchanged between 1800 and 2008.

how to execute it with the limited power available, how to lower energy expenditures—and the metabolic cost of thinking, even very hard thinking, is very small compared to strenuous muscular exertion. On the other hand, mental development requires years of language acquisition, socialization, and learning by mentoring and the accumulation of experience, and as societies progressed, this learning process became more demanding and longer lasting through formal schooling and training, services that have come to require considerable indirect energy inputs to support requisite physical infrastructures and human expertise.

A circle is closed. I have noted the necessity of quantitative evaluations, but the real understanding of energy in history requires much more than reducing everything to numerical accounts in joules and watts and treating them as all-encompassing explanations. I will approach the challenge in both ways: I will note energy and power requirements and densities and point out improving efficiencies, but I will not ignore the many qualitative attributes that constrain or promote specific energy uses. And while the imperatives of energy needs and uses have left a powerful imprint on history, many details, sequences, and consequences of these fundamental evolutionary determinants can be explained only by referring to human motivations and preferences, and by acknowledging those surprising, and often seemingly inexplicable, choices that have shaped our civilization's history.

2 Energy in Prehistory

Understanding the origins of the genus *Homo* and filling in the details of its subsequent evolution is a never-ending quest as new findings push back many old markers and complicate the overall picture with the discovery of species that do not fit easily into an existing hierarchy (Trinkaus 2005; Reynolds and Gallagher 2012). In 2015 the oldest reliably dated hominin remains were those of *Ardipithecus ramidus* (4.4 million years ago, found in 1994) and *Australopithecus anamensis* (4.1–5.2 million years ago, found in 1967). A notable 2015 addition was *Australopithecus deyiremeda* (3.3–3.5 million years ago) from Ethiopia (Haile-Selassie et al. 2015). The sequence of younger hominins includes *Australopithecus afarensis* (unearthed in 1974 in Laetoli, Tanzania, and in Hadar, Ethiopia), *Homo habilis* (discovered in 1960 in Tanzania), and *Homo erectus* (beginning 1.8 million years ago, with many finds in Africa, Asia, and Europe extending to about 250,000 years ago).

Reanalysis of the first *Homo sapiens* bones—Richard Leakey's famous discoveries in Ethiopia starting in 1967—dated them to about 190,000 years ago (McDougall, Brown, and Fleagle 2005). Our direct ancestors thus spent their lives as simple foragers, and it was only about 10,000 years ago that the first small populations of our species began a sedentary existence based on the domestication of plants and animals. This means that for millions of years, the foraging strategies of hominins resembled those of their primate ancestors, but we now have isotopic evidence from East Africa that by about 3.5 million years ago hominin diets began to diverge from those of extant apes. Sponheimer and co-workers (2013) showed that after that time, several hominin taxa began to incorporate ^{13}C-enriched foods (produced by C_4 or crassulacean acid metabolism) in their diets and had a highly variable carbon isotope composition atypical of African mammals. Reliance on C_4 plants is thus of ancient origin, and in modern agriculture two C_4 cultivars, partly offset by a reduced gastrointestinal tract (Braun et al. 2010). While extant nonhuman primates have more than 45% of their gut mass in the colon and only 14–29% in the small intestine, in humans those shares are reversed, with more than 56% in the small intestine and only 17–25% in the colon, a clear indication of adaptation to high-quality, energy-dense foods (meat, nuts) that can be digested in the small intestine. Increased meat consumption also helps to explain human gains in body mass and height, as well as smaller jaws and teeth (McHenry and Coffing 2000; Aiello and Wells 2002). But a higher meat intake could not change the energy basis of evolving hominins: to secure any food they had to rely only on their muscles and on simple stratagems while gathering, scavenging, hunting, and fishing.

Tracing the genesis of the first wooden tools (sticks and clubs) is impossible as only those artifacts that were preserved in anoxic environments, most commonly in bogs, were able to survive for extended periods. Disintegration is not a problem with the hard stones used to fashion simple tools, and new findings have been pushing back the date of the earliest verifiable hominin stone tools. For several decades the consensus dated the earliest stone tools to about 2.5 million years ago. Cobble-based, these relatively small and simple Oldowan hammerstones (cores with an edge), choppers, and flakes made it much easier to butcher animals and to break their bones (de la Torre 2011). But the latest findings at the Lomekwi site in West Turkana, Kenya, pushed the date of the oldest known stone toolmaking to about 3.3 million years ago (Harmand et al. 2015).

About 1.5 million years ago hominins started to quarry larger flakes to make bifacial hand axes, picks, and cleavers of Acheulean (1.2–0.1 million years ago) style. The chipping of a single core yielded sharp cutting edges less than 20 cm long, and these practices produced a large variety of special handheld stone tools (fig. 2.1). Wooden spears were essential for hunting larger animals. In 1948 a nearly complete spear found inside an elephant skeleton in Germany was dated to the last interglacial period (115,000–125,000 years ago), and in 1996 throwing spears found at a Schöningen open-cast lignite mine were dated to 400,000–380,000 years ago (Thieme 1997), and stone points were hafted to wooden spears beginning about 300,000 years ago.

But new discoveries in South Africa put the earliest date of making hafted multicomponent tools about 200,000 years earlier than previously reported: Wilkins and co-workers (2012) concluded that stone points from Kathu Pan, made about 500,000 years ago, functioned as spear tips. True long-range projectile weaponry evolved in Africa between 90,000 and

Figur
Acheulean stone tools, first made by *Homo ergaster,* were formed by the removal of stone flakes to create specialized cutting blades (Corbis).

70,000 years ago (Rhodes and Churchill 2009). Another recent South African discovery showed that a significant technical advance—the production of small bladelets (microliths), primarily from heat-treated stone, to be used in making composite tools—took place as early as 71,000 years ago (Brown et al. 2012). Larger composite tools became common only about 25,000 years ago (Europe's Gravettian period) with the production of ground and hafted adzes and axes, and with the more efficient flaking of flint, yielding many sharp-edged tools; harpoons, needles, saws, pottery, and items from woven fibers (clothes, nets, baskets) were also invented and adopted during that time.

Magdalenian techniques (between 17,000 and 12,000 years ago; the era is named after a rock shelter at La Madeleine in southern France where the tools were discovered) produced up to 12 m of microblade edges from a single stone, and experiments with their modern replicas (mounted on spears) show their hunting efficacy (Pétillon et al. 2011). A stone-tipped spear became an even more potent weapon after the invention of spear throwers during the late Paleolithic. A leveraged throw easily doubled the velocity of the weapon and reduced the necessity for a closer approach. Stone-tipped arrows carried these advantages further, with an added gain in accuracy.

We will never know the earliest dates for the controlled use of fire for warmth and cooking: in the open, any relevant evidence was removed by many subsequent events, and in occupied caves it was destroyed by generations of later use. The earliest date for a well-attested use of controlled fire has been receding: Goudsblom (1992) put it at about 250,000 years ago; and a dozen years later Goren-Inbar and co-workers (2004) pushed it as far back as 790,000 years ago, while the fossil record suggests that the consumption of some cooked food took place as early as 1.9 million years ago. But without any doubt, by the Upper Paleolithic—30,000 to 20,000 years ago, when *Homo sapiens sapiens* displaced Europe's Neanderthals—the use of fire was widespread (Bar-Yosef 2002; Karkanas et al. 2007).

Cooking has been always seen as an important component of human evolution, but Wrangham (2009) believes that it had a "monstrous" effect on our ancestors because it greatly expanded the range and quality of available food, and also because its adoption brought many physical changes (including smaller teeth and a less voluminous digestive tract) and behavioral adjustments (such as the need to defend stores of accumulated food, which promoted protective female-male bonds) that led eventually to complex socialization, sedentary lives and "self-domestication." All prehistoric cooking was done with open fires, with meat suspended above the flames, buried in hot embers, placed on hot rocks, encased in a tough skin, covered by clay, or put with hot stones into leather pouches filled with water. Owing to the variety of settings and methods, it is impossible to quote typical fuel conversion efficiencies. Experiments show that 2–10% of wood's energy ends up as useful heat for cooking, and plausible assumptions indicate annual wood consumption maxima of 100–150 kg/year/capita (box 2.1).

Box 2.1

Wood consumption in open-fire cooking of meat

Realistic assumptions for setting plausible maxima of wood consumption in open-fire meat cooking during the late Paleolithic are as follows (Smil 2013a): average daily food energy intake of 10 MJ/capita (adequate for adults, higher than the mean for entire populations), with meat being 80% (8 MJ) of the total food intake; a food energy density of animal carcasses of 8–10 MJ/kg (typical for mammoths, generally 5–6 MJ/kg for large ungulates); an average ambient temperature of 20°C in warm and a mean of 10°C in colder climates; cooked meat at 80°C (77°C suffices for well-done meat); a heat capacity of meat of about 3 kJ/kg°C; cooking efficiency of an open fire at just 5%; and an average energy density of air-dried wood of 15 MJ/kg. These assumptions imply an average daily per capita intake of nearly 1 kg of mammoth meat (and about 1.5 kg of large ungulate meat) and a daily need for about 4–6 MJ of wood. The annual total would be 1.5–2.2 GJ or 100–150 kg of (some fresh and some air-dried) wood. For 200,000 people who lived 20,000 years ago the global need would be 20,000–30,000 t, a negligible share (on the order of 10^{-8}) of the standing pre-agricultural woody phytomass.

In addition to warming and cooking, fire was also used as an engineering tool: modern humans were heat-treating stones to improve their flaking properties as early as 164,000 years ago (Brown et al. 2009). And Mellars (2006) suggested there is evidence for the controlled burning of vegetation in South Africa as early as 55,000 years ago. Woodland burning as a tool of environmental management by foragers during the early Holocene would have been done to aid hunting (by promoting the regrowth of forage to attract animals and improving visibility), to make human mobility easier, or to improve or synchronize the gathering of plant foods (Mason 2000).

The great spatial and temporal variability of the archaeological record precludes making any simple generalizations concerning the energy balances of prehistoric societies. Descriptions of first contacts with surviving foragers and their anthropological studies provide uncertain analogies: information on groups that survived in extreme environments long enough to be studied by modern scientific methods offers a limited insight into the lives of prehistoric foragers in more equable climates and more fertile areas. Moreover, many studied foraging societies were already affected by prolonged contact with pastoralists, farmers, or overseas migrants (Headland and Reid 1989; Fitzhugh and Habu 2002). But the absence of a typical foraging pattern does not preclude recognition of a number of biophysical imperatives governing energy flows and determining the behavior of gathering and hunting groups.

Foraging Societies

The most comprehensive collections of reliable evidence show that the average population densities of modern foraging populations—reflecting a variety of natural habitats and food acquisition skills and techniques—ranged over three orders of magnitude (Murdock 1967; Kelly 1983; Lee and Daily 1999; Marlowe 2005). The minima were less than a single person/100 km^2 to several hundred people/100 km^2, with the global mean of 25 people/100 km^2 for 340 studied cultures, too low to support more complex societies with increasing functional specialization and social stratification. The average densities of foragers were lower than the densities of similarly massive herbivorous mammals that were able to digest abundant cellulosic phytomass.

Whereas allometric equations predict about five 50 kg mammals/km^2, chimpanzee densities are between 1.3 and 2.4 animals/km^2, and the densities of hunter-gatherers surviving into the twentieth century were well below one person/km^2 in warm climates, only 0.24 in the Old World and 0.4 in the New World (Marlowe 2005; Smil 2013a). Population densities were significantly higher for groups combining the gathering of abundant plants with hunting (well-studied examples include groups in postglacial Europe and, more recently, in the basin of Mexico) and for coastal societies heavily dependent on aquatic species (with well-documented archaeological sites in the Baltic region and more recent anthropological studies in the Pacific Northwest).

Mollusk collecting, fishing, and near-shore hunting of sea mammals sustained the highest foraging densities and led to semipermanent, even permanent, settlements. The coastal villages of the Pacific Northwest, with their large houses and organized communal hunting of sea mammals, were exceptional in their sedentism. These large density variations were not a simple function of biospheric energy flows: they were not uniformly decreasing poleward and increasing equatorward (in proportion to higher photosynthetic productivity), or corresponding to the total mass of animals available for hunting. They were determined by ecosystemic variables, by a relative dependence on plant and animal foods, and by the use of seasonal storage. Much like nonhuman primates, all foragers were omnivorous, but killing larger animals was a major energetic challenge as it targeted a much

Box 2.2

Harvesting Brazil nuts

Because of their high lipid content (66%), Brazil nuts contain about 27 MJ/kg (compared to about 15 MJ/kg for cereal grains), are about 14% protein, and are also a source of potassium, magnesium, calcium, phosphorus, and high levels of selenium (Nutrition Value 2015). Harvesting the nuts is both demanding and dangerous. *Bertholletia excelsa* grows up to 50 m, with individual trees widely scattered. Between 8 and 24 nuts are contained in heavy (up to 2 kg) capsules covered with a coconut-like hard endocarp. Nut foragers must time their harvest: too early, and the pods are still inaccessible in the canopies and gatherers must waste energy on another trip; too late, and agoutis (*Dasyprocta punctata*), which are large rodents and the only animals able to open the fallen pods, will eat the seeds right away or bury some of them in food caches (Haugaasen et al. 2010).

Cavallo 1992; Pobiner 2015). Large predators—lions, leopards, saber-toothed cats—often left behind partially eaten herbivore carcasses. This meat, or at least the nutritious bone marrow, could be reached by alert early humans before it was devoured by vultures, hyenas, and other scavengers. But Domínguez-Rodrigo (2002) has argued that scavenging would not provide enough meat and that only hunting could secure sufficient animal protein on grasslands. In any case, human bipedalism and ability to sweat better than any other mammal made it also possible to chase to exhaustion even the fastest herbivores (box 2.3).

Carrier (1984) believes that the outstanding rates of human heat dissipation provided a notable evolutionary advantage that served our ancestors well in appropriating a new niche, that of diurnal, hot-temperature predators. The human ability to sweat profusely and hence to work hard in hot environments was retained by populations that migrated to colder climates: there are no major differences in the density of eccrine glands among populations of different climate zones (Taylor 2006). People from middle and high latitudes can match the sweating rates of hot-climate natives after a short period of acclimatization.

But once adequate tools were invented and adopted, hunting with them was preferable to running down the prey, and Faith (2007) confirmed, after examining 51 assemblages from the Middle Stone Age and 98 from the Later Stone Age, that early African hunters were fully competent at killing large ungulate animals, including buffaloes. The energy imperatives of

Box 2.3

Running and heat dissipation by humans

All quadrupeds have optimum speeds for different gaits, such as walk, trot, and canter in horses. The energy cost of human running is relatively high compared to the running cost of similarly massive mammals, but unlike them, humans can uncouple that cost from running speed for common velocities between 2 and 6 m/s (Carrier 1984; Bramble and Lieberman 2004). Bipedalism and efficient heat dissipation explain this feat. Quadrupedal ventilation is limited to one breath per locomotor cycle. The thoracic bones and muscles must absorb the impact on the front limbs as the dorsoventral binding rhythmically compresses and expands the thorax, but human breath frequency can vary relative to stride frequency: humans can run at a variety of speeds, whereas optimal quadruped speed is structurally determined.

The extraordinary human ability to thermoregulate rests on very high rates of sweating. Horses lose water at an hourly rate of 100 g/m^2 of their skin, and camels lose up to 250 g/m^2, but people lose more than 500 g/m^2, with peak rates of more than 2 kg/hour (Torii 1995; Taylor and Machado-Moreira 2013). Perspiration rate translates to heat loss of 550–625 W, enough to regulate temperature even during extremely hard work. People can also drink less than they perspire, and make up for any temporary partial dehydration hours later. Running turned humans into diurnal, high-temperature predators that could chase animals to exhaustion (Heinrich 2001; Liebenberg 2006). Documented chases include those of the Tarahumara Indians of northern Mexico running down deer and of Paiutes and Navajos besting pronghorn antelopes. The Kalahari Basarwa could chase duikers, gemsbok, and, during the dry season, even zebras to exhaustion, as some Australian Aborigines did with kangaroos. Hunters running barefoot reduced their energy costs by about 4% (and had fewer acute ankle and chronic lower leg injuries) than modern runners with athletic shoes (Warburton 2001).

hunting large animals had also made an incalculable contribution to human socialization. Trinkaus (1987, 131–132) concluded that “most of the distinguishing human characteristics, such as bipedalism, manual dexterity, and elaborate technology, and marked encephalization can be viewed as having been promoted by the demands of an opportunistic foraging system.”

Hunting’s role in the evolution of human societies is self-evident. Individual success in hunting large animals with primitive weapons was unacceptably low, and viable hunting groups had to maintain minimum cooperative sizes in order to track wounded animals, butcher them, transport their meat, and then pool the gains. Communal hunting brought by far the greatest rewards, with well-planned and well-executed herding of animals into confined runs (using brush and stone drive lines, wooden fences, or ramps) and capturing them in prepared pens or natural traps, or—perhaps the simplest and most ingenious solution—stampeding them over cliffs (Frison 1987). Many large herbivores—mammoths, bison, deer, antelopes, mountain sheep—could be slaughtered in such ways, providing caches of frozen or processed (smoked, pemmican) meat.

Head-Smashed-In Buffalo Jump near Fort Mcleod, Alberta, a UNESCO World Heritage Site, is one of the more spectacular sites of this inventive hunting strategy, which was used at the site for about 5,700 years. "To start the hunt ... young men ... would entice the herd to follow them by imitating the bleating of a lost calf. As the buffalo moved closer to the drive lanes (long lines of stone cairns were built to help the hunters direct the buffalo to the cliff kill site), the hunters would circle behind and upwind of the herd and scare the animals by shouting and waving robes" and stampeded the herd over the cliff (UNESCO 2015a). The net energy return in animal protein and fat was high. Late Pleistocene hunters may have become so skillful that many students of the Quaternary era concluded that hunting was largely (even completely) responsible for a relatively rapid disappearance of the late Paleolithic megafauna, animals with a body mass greater than 50 kg (Martin 1958, 2005; Fiedel and Haynes 2004), but the verdict remains uncertain (box 2.4).

Box 2.4

Extinction of the Late Pleistocene megafauna

The persistent killing of slow-breeding animals (those with a single offspring born after a long gestation) could lead to their extinction. If we assume that Late Pleistocene foragers had a high daily food requirement of 10 MJ/capita, that they ate mostly meat, and that most of it (80%) came from megafauna, then their population of two million people would need nearly 2 Mt (fresh weight) of meat (Smil 2013a). If mammoths were the only hunted species, that would have required the annual killing of 250,000–400,000 animals. Megaherbivore hunting also targeted other large mammals (elephants, giant deer, bison, aurochs), and procuring 2 Mt of meat from a mixture of these species would have required an annual kill of some two million animals. A more likely explanation for the Late Pleistocene extinctions is a combination of natural (climate and vegetation change) and anthropogenic (hunting and fire) factors (Smil 2013a).

All pre-agricultural societies were omnivorous; they did not have the luxury of ignoring any available food resource. Although foragers ate a large variety of plant and animal species, usually only a few principal foodstuffs dominated their diets. A preference for seeds among gatherers was inevitable. Besides being rather easy to collect and store, seeds combine a high energy content with relatively high protein shares. Wild grass seeds have as much food energy as cultivated grains (wheat is at 15 MJ/kg), while nuts have an energy density up to about 80% higher (walnuts contain 27.4 MJ/kg).

All wild meat is an excellent source of protein, but most of it contains very little fat, and hence it has very low energy density—less than half that of grains for small, lean mammals. Not surprisingly, there was a widespread hunting preference for large and relatively fatty species. A single small mammoth provided as much edible energy as 50 reindeer, while a bison was easily equal to 20 deer (box 2.5). This is why our Neolithic ancestors were willing to ambush huge mammoths with their simple stone-tipped weapons, or why Indians on the North American plains, seeking fatty meat for preparing long-lasting pemmican, spent so much energy in pursuing bison.

But energy considerations alone cannot provide a full explanation of foraging behavior. If they were always dominant, then optimal foraging—whereby gatherers and hunters try to maximize their net energy gain by minimizing the time and effort spent in foraging—would have been their universal strategy (Bettinger 1991). Optimal foraging explains the preference for hunting large, fatty mammals or for collecting less nutritious plant parts that do not need processing rather than energy-dense nuts, which may be hard to crack. Many foragers undoubtedly behaved in ways that maximized their net energy return, but other existential imperatives often worked against such behavior. Among the most important ones were the availability of safe night shelters, the need to defend territories against competing groups, and the needs for reliable water sources and for vitamins and minerals. Food preferences and attitudes toward work were also important (box 2.6).

Our inability to reconstruct prehistoric energy balances has provoked some inadmissible generalizations. For some groups the total foraging effort was relatively low, only a few hours a day. This finding led to foragers being portrayed as "the original affluent society," living in a kind of material plenty filled with leisure and sleep (Sahlins 1972). Most notably, Dobe !Kung people of the Kalahari Desert in Botswana, living on wild plants and meat, were thought to provide an excellent window on the lives of

Box 2.5

Body masses, energy densities, and food energy content of hunted animals

Animals	Body mass (kg)	Energy density (MJ/kg)	Food energy per animal (MJ)
Whales	5,000–40,000	25–30	80,000–800,000
Large proboscids (elephants, mammoths)	500–4,000	10–12	2,500–24,000
Large bovids (aurochs, bison)	200–400	10–12	1,000–2,400
Large cervids (elk, reindeer)	100–200	5–6	250–600
Seals	50–150	15–18	500–1,800
Small bovids (deer, gazelle)	10–60	5–6	25–180
Large monkeys	3–10	5–6	5–30
Lagomorphs (hares, rabbits)	1–5	5–7	3–17

Notes: I assume that the edible portion is two-thirds of the body mass of whales and seals and half of the body mass of other animals. The average energy density for whales I calculated by assuming that 25% of their body mass is blubber.

Sources: Based on data in Sanders, Parsons, and Santley (1979), Sheehan (1985), and Medeiros and co-workers (2001).

prehistoric foragers, who allegedly led contented, healthy, and vigorous lives (Lee and DeVore 1968). This conclusion, based on very limited and dubious evidence, must be—and has been—challenged (Bird-David 1992; Kaplan 2000; Bogin 2011.

Simplistic theorizing about affluent foragers ignored both the reality of much of the hard and often dangerous work in foraging and the frequency with which environmental stresses and infectious diseases ravaged most foraging societies. Seasonal food shortages forced the eating of unpalatable plant tissues and led to weight loss, and often to devastating famines. They also resulted in high infant mortality (including infanticide) and promoted low fertility rates. And, not surprisingly, a reanalysis of energy expenditure and demographic data collected in the 1960s found that the nutritional southerly open tundra or steppelike vegetation, which supported herbivorous herds larger than anywhere in periglacial Europe (Mellars 1985). The complexity of these Paleolithic cultures is best attested by their remarkable sculptures, carvings, and cave paintings (Grayson and Delpech 2002; French and Collins 2015) (fig. 2.3).

The highest productivities in complex foraging were associated with the exploitation of aquatic resources (Yesner 1980). Excavations of Mesolithic sites in southern Scandinavia showed that once the postglacial hunters had depleted the stocks of large herbivores they became hunters of porpoises and whales, fishers, and collectors of shellfish (Price 1991). They lived in larger, often permanent settlements that included cemeteries. Northwestern Pacific tribes dependent on fishing had settlements of several hundred people living in well-built wooden houses. Regular runs of salmon species guaranteed a reliable and easily exploitable resource that could be safely stored (smoked) to provide excellent nutrition. Thanks to its high fat content (about 15%), salmon has an energy density (9.1 MJ/kg) nearly three

Charcoal paintings of animals on a wall of the Chauvet Cave in southern France. These remarkable likenesses were dated to between 32,900 and 30,000 years ago (Corbis).

times that of cod (3.2 MJ/kg). The superior case of high population density dependent on maritime hunting is that of northwestern Alaskan Inuit, whose net energy returns in killing migrating baleen whales were more than 2,000-fold (Sheehan 1985) (box 2.8).

A food supply dependent on a few seasonal energy flows required extensive, and often elaborate, storage. Storage practices included caching in permafrost; drying and smoking of seafood, berries, and meats; storing of seeds and roots; preservation in oil; and the making of sausages, nut-meal cakes, and flours. Large-scale, long-term food storage changed foragers' attitudes toward time, work, and nature and helped stabilize populations at higher densities (Hayden 1981; Testart 1982; Fitzhugh and Habu 2002). The need to plan and budget time was perhaps the most important evolutionary benefit. This new mode of existence precluded frequent mobility and introduced a different way of subsistence based on surplus accumulation. The process was self-amplifying: the quest for the manipulation of an ever larger share of solar energy flows set the societies on the road toward higher complexity.

Box 2.8
Alaskan whalers

In less than four months of near-shore hunting of baleen whales, whose migration routes led along the Alaskan coast, men in umiak (boats with a driftwood or whalebone frame covered with sealskin and crewed by up to eight people) amassed food for settlements whose precontact population reached almost 2,600 people (Sheehan 1985; McCartney 1995). The largest adult baleen whales weigh up to 55 t, but even the most commonly landed immature two-year-old animals averaged nearly 12 t. The high energy density of blubber (about 36 MJ/kg) and muktuk (skin and blubber, which also has a vitamin C content comparable to that of grapefruit) resulted in a more than 2,000-fold energy gain in hunting.

Lower but still exceptionally high energy returns resulted from exploiting annual salmon runs by the coastal tribes of the Pacific Northwest: the density of fish returning upstream was often so high that fishers could simply scoop them into boats or onto the shore. These high energy returns supported large permanent settlements, social complexity, and artistic creativity (large wooden totems). Eventual limits on the population growth of these coastal settlements were imposed by the necessity to hunt other marine species and land game in order to secure raw materials for clothing, bedding, and hunting equipment.

Although our understanding of hominin evolution has increased impressively during the last two generations, one key area of uncertainty remains: contrary to all popular claims about the benefits of Paleolithic diets, we still cannot reconstruct the representative composition of preagricultural subsistence. This should not be a surprise (Henry, Brooks, and Piperno 2014). Readily degradable plant remains of food consumption very rarely survive for tens of thousands of years and almost never for millions, making it exceedingly difficult to quantify the share of plant foods in typical diets. Bones often survive, but their accumulations from animal predations must be carefully distinguished from hominin acquisition, and even then it is impossible to interpret how representative they were of particular diets.

As Pryor and co-workers (2013) note, the widely accepted image of European Upper Paleolithic hunter-gatherers as proficient hunters of large mammals inhabiting largely treeless landscapes stems from the poor preservation of plant remains at such ancient sites. Their study showed that the potential of such sites to provide macrofossil remains of plants consumed by humans has been underestimated, and that "the ability to exploit plant foods may have been a vital component in the successful colonisation of these cold European habitats" (Pryor et al. 2013, 971). And Henry, Brooks, and Piperno (2014) analyzed plant microremains—starch grains and phytoliths—left in dental calculus and on stone tools and concluded that both modern humans and their Neanderthal coevals consumed a similarly wide range of plant foods, including rhizomes and grass seeds.

Changes in body height and mass and in cranial features (gracilization of the mandible) are indirect indicators of prevailing diets and could have arisen from a variety of food mixtures. The findings of stone tools used to kill and butcher animals cannot be readily related to average per capita meat intake over extended periods of time, and hence only direct stable isotope evidence (ratios of $^{13}C/^{12}C$ and $^{15}N/^{14}N$) provides an accurate determination of long-term protein sources, their trophic levels, and their terrestrial and marine origins; distinguishes phytomass synthesized by the two principal pathways (C_3 and C_4) and heterotrophs feeding on those plants; and informs us about the basic makeup of the total diet. Even these studies cannot be translated into reliable patterns of average macronutrient (carbohydrates, proteins, lipids) intake, but isotope data indicate that during the Gravettian period in Europe, animal protein was the main source of dietary protein, with aquatic species contributing about 20% of the total, and even more at coastal sites (Hublin and Richards 2009).

Before leaving the forager energetics I should note that foraging retained an important role in all early agricultural societies. In Çatalhöyük, a large Neolithic agricultural settlement on the Konya Plain dated to about 7200 BCE, early farmers had diets dominated by grains and wild plants, but excavations also show the bones of hunted animals, ranging from large aurochs to foxes, badgers, and hares (Atalay and Hastorf 2006). And at Tell Abu Hureyra in northern Syria, hunting remained a critical source of food for 1,000 years after the beginning of plant domestication (Legge and Rowley-Conwy 1987). In predynastic Egypt (earlier than 3100 BCE), the cultivation of emmer wheat and barley was complemented by the hunting of waterfowl, antelopes, wild pigs, crocodiles, and elephants (Hartmann 1923; Janick 2002).

Origins of Agriculture

Why did some foragers start to farm? Why did these new practices diffuse so widely, and why did their adoption proceed at what, in evolutionary terms, is a fairly rapid rate? These challenging questions may be sidestepped by agreeing with Rindos (1984) that agriculture has no single cause but arose from a multitude of interdependent interactions. Or, as Bronson (1977, 44) put it, "What we are dealing with is a complex, multifaceted adaptive system, and in human adaptive systems ... single all-efficient 'causes' cannot exist." But many anthropologists, ecologists, and historians have been trying to find precisely such principal causes, and there are many publications surveying diverse explanatory theories about the origin of agriculture (Cohen 1977; Pryor 1983; Rindos 1984; White and Denham 2006; Gehlsen 2009; Price and Bar-Yosef 2011).

Overwhelming evidence for the evolutionary character of agricultural advances makes it possible to narrow down the possibilities. The most persuasive explanation of agricultural origins lies in the combination of population growth and environmental stress, in recognizing that the transition to permanent cropping was driven by both natural and social factors (Cohen 1977). Because the climate was too cold and CO_2 levels were too low during the late Paleolithic and because these conditions changed with the subsequent warming, Richerson, Boyd, and Bettinger (2001) have argued that agriculture was impossible during the Pleistocene but mandatory during the Holocene. This argument is strengthened by the fact that between 10,000 and 5,000 years before the present, cropping evolved independently in at least seven locations on three continents (Armelagos and Harper 2005).

Fundamentally, crop cultivation is an effort to ensure an adequate food supply, and hence agriculture's origins could be fully explained as yet another instance of an energy imperative. Diminishing returns from gathering and hunting led to the gradual extension of incipient cultivation present in many foraging societies. As already noted, foraging and cultivation coexisted in various shares of food output for very long periods. But no sensible explanation of agriculture's origins can ignore the many social advantages of farming. Sedentary crop cultivation was an efficient way for more people to stay together; it made it easier to have larger families, to accumulate material possessions, and to organize for both defense and offense.

Orme (1977) even concluded that food production may have been unimportant as an end in itself, but there is no doubt that both the genesis and diffusion of agriculture had critical social cofactors. Any simplistic energy-driven explanation of agricultural origins is also weakened by the fact that the net energy returns of early farming were often inferior to those of earlier or concurrent foraging activities. Compared to foraging, early farming usually required higher human energy inputs—but it could support higher population densities and provide a more reliable food supply. This explains why so many foraging societies had continuous interaction (and often much trade) with neighboring farming groups for thousands, or at least hundreds, of years before they adopted permanent farming (Headland and Reid 1989).

There was no single center of domestication from which cultivated plants and milk- and meat-producing animals spread, but in the Old World the most important region of agricultural origin was not, as previously thought, the southern Levant but rather the upper reaches of the Tigris and Euphrates rivers (Zeder 2011). This means that food production started along the margins, rather than in the core areas, of optimal zones. The botanical record from Chogha Golan in the foothills of the Iranian Zagros Mountains provides the most recent confirmation of this reality (Riehl, Zeidi, and Conard 2013): cultivation of wild barley (*Hordeum spontaneum*) began there about 11,500 years ago, later augmented by the cultivation of wild wheat and wild lentils.

In process terms, it is essential to stress that there are no clear thresholds or sharp divides between foraging and agriculture, as extended periods of managing wild plants and animals precede their true domestication, which is characterized by clearly identifiable morphological changes. And, contrary to earlier understandings, the domestication of plants and animals proceeded almost concurrently and yielded an effective study found returns no higher than 6- to 10-fold (Norgan et al. 1974)—but the corn harvest of Kekchi Maya (Guatemala) brought at least a 30-fold energy return (Carter 1969). Most net returns were 11–15 for small grains and 20–40 for most root crops, bananas, and also for corn, while maxima were close to 70 for some roots and legumes (box 2.9). Feeding one person required mostly 2–10 ha of land to be cleared periodically, with the actually cultivated area ranging from just 0.1 to 1 ha/person. Even moderately productive shifting agriculture supported population densities an order of magnitude higher than the best foraging.

Where scarcity of precipitation, or its long seasonal absence, made cropping unrewarding or impossible, nomadic pastoralism has been an effective alternative (Irons and Dyson-Hudson 1972; Galaty and Salzman 1981; Evangelou 1984; Khazanov 2001; Salzman 2004). Managed grazing has been the energetic foundation of scores of Old World societies, and though some of them remained poor and isolated, others were among the most feared long-distance interveners in history: Xiongnu were in conflict with the early Chinese dynasties for hundreds of years, and the Mongol invasion of 1241 reached as far west as today's Poland and Hungary.

Animal husbandry is a form of prey conservation, a strategy of deferred harvests whose opportunity costs are greater for larger animals, especially

Box 2.9

Energy costs and population densities in shifting cultivation

Net energy cost is used to calculate returns of shifting farming. I assume that an average labor input requires 700 kJ/h. Outputs are edible harvests uncorrected for storage losses and seed needs.

Populations	Main crops	Energy inputs (hours)	Energy returns	Population densities (people/ha)
Southeast Asia	Tubers	2,000–2,500	15–20	0.6
Southeast Asia	Rice	2,800–3,200	15–20	0.5
West Africa	Millet	800–1,200	10–20	0.3–0.4
Mesoamerica	Corn	600–1,000	25–40	0.3–0.4
North America	Corn	600–800	25–30	0.2–0.3

Sources: Calculated from data in Conklin (1957), Allan (1965), Rappaport (1968), Carter (1969), Clark and Haswell (1970), Heidenreich (1971), Thrupp and co-workers (1997), and Coomes, Girmard, and Burt (2000).

bovids (Alvard and Kuznar 2001). Larger animals are preferred, but higher growth rates favor sheep and goats. Animals can convert grasses into milk, meat, and blood with remarkably low inputs of human energy (fig. 2.5). Pastoralists' labor was confined to herding the animals, guarding them against predators, watering them, helping with deliveries, milking regularly, and butchering infrequently, and sometimes building temporary enclosures. The sustainable population densities of such societies were no higher than those of foraging groups (box 2.10).

For millennia, nomadic grazing dominated parts of Europe and the Middle East, and large regions of Africa and Asia. In all of these places it sometimes blended into mixtures of seminomadic agropastoralism, especially in parts of Africa with a significant component of foraging. Often hemmed in by more productive farmers, and commonly dependent on barter with settled societies, some of these nomads had little impact beyond their confined worlds. But many groups exercised great influence on the Old World's history through their repeated invasions and temporary conquests of agricultural societies (Grousset 1938; Khazanov 2001). Some pure pastoralists and agropastoralists survive even today—above all in Central Asia and in Sahelian and eastern Africa—but it has been an increasingly marginal existence.

Maasai herder with his cattle (Corbis).

Box 2.10
Nomadic pastoralists

Helland (1980) illustrated low labor requirements in pastoral societies by pointing out the large numbers of major livestock species managed by a single herder in the East African setting: up to 100 camels, 200 cattle, and 400 sheep and goats. Khazanov (1984) lists similarly large figures for Asian pastoralists: two mounted shepherds for 2,000 sheep in Mongolia, an adult shepherd and a boy to tend 400–800 cattle in Turkmenia. The appeal of low labor needs was one of the key reasons for the reluctance of many pastoralists to abandon their peregrinations and to become settled farmers. As a result, many nomadic societies existed for generations as neighbors of sedentary farmers and abandoned their herds only because of devastating drought or substantial loss of available pastures.

Minimum per capita counts for pastoral subsistence were 5–6 heads of cattle, 2.5 3 camels, or 25–30 goats or sheep. Much higher cattle ownership among traditional Maasai (13–16 heads/capita) is explained by the minimum requirements for blood harvesting, done by piercing a tightened jugular vein and drawing 2–4 L every 5–6 weeks. During the periods of drought a herd of 80 cattle was needed to provide blood for a family of 5–6 people, or 13–16 animals/capita (Evangelou 1984). In all cases, nomadic population densities were low compared with those of settled farmers, in East Africa mostly between 0.8–2.2 people/km^2, and 0.03–0.14 heads/ha (Helland 1980; Homewood 2008).

3 Traditional Farming

While the transition from foraging to farming cannot be explained solely by energetic imperatives, the evolution of agriculture can be seen as a continuing effort to raise land productivity (to increase digestible energy yield) in order to accommodate larger populations. Even within that narrowed framework, important nonenergy considerations (such as an adequate supply of micronutrients, vitamins, and minerals) should not be forgotten, but because of the overwhelmingly vegetarian diets of all traditional peasant societies it is not a distorting simplification to focus on the output of digestible energy produced in staple crops in general and grains in particular.

Only grains combine fairly high yields—initially only about 500 kg/ha; eventually, in the most intensive traditional agricultures, more than 2 t/ha—with high shares of easily digestible carbohydrates and a moderately high level of proteins (some, above all corn, also have a significant amount of lipids). Their energy density at maturity (15–16 MJ/kg) is roughly five times that of fresh tubers, and their moisture content when air-dried is low enough to allow long-term storage (in vessels by households, on a large scale in granaries). Staple grains also mature fast enough—traditional varieties mature in 100–150 days—to permit increased food productivity through annual rotations with other crops (mainly oilseeds and grain legumes) or by double-cropping of cereals.

Boserup (1965, 1976) conceptualized the link between food energy and the evolution of peasant societies as a matter of choices. Once a particular agricultural system reaches the limits of its productivity, people can decide to migrate, to stay and stabilize their numbers, to stay and let their numbers decline—or to adopt a more productive way of farming. The last option may not be necessarily more appealing or more probable than the other solutions, and its adoption is often postponed or chosen only reluctantly because such a shift almost invariably requires higher energy inputs—in most cases of both human and animal labor. Increased productivity will repeatedly with individual peasant families or villages. But the increasing scale of such activities eventually demanded hierarchical coordination and supralocal management. And the need for more powerful energy sources to process larger amounts of grain and oilseeds for growing cities was an important stimulus for the development of the first important substitutes for human and animal muscles, the use of water and wind flows for grain milling and oilseed pressing. Millennia of farming evolution resulted in a wide range of operating modes and productivities within the constraints of shared agronomic practices and common energetic imperatives.

Principal commonalities included basic field and postharvest operations, a widespread dominance of cereals in cropping, and sequences of production cycles that were determined largely by environmental conditions. Four major steps toward the intensification of traditional farming were a more efficient use of animal labor, advances in irrigation, increasing fertilization, and crop rotation and multicropping. Despite many environmental and technical constraints, traditional agricultures could support population densities that were orders of magnitude higher than those of all but a few foraging societies. Relatively early in their existence they began creating an energy surplus that allowed initially small but significant numbers of adults to engage in an expanding range of nonfarming activities, which eventually led to highly diversified and stratified preindustrial societies. Productive limits on traditional agricultures were removed only by rising inputs of fossil fuels, an energy subsidy that reduced agricultural labor to only a small fraction of the total labor force and enabled the rise of modern high-energy urban societies.

Commonalities and Peculiarities

The requirements of crop growing imposed a general pattern on the sequence of field work. Cultivation of identical crops led to the invention or adoption of very similar agronomic practices, tools, and simple machines. Some of these innovations came early, diffused rapidly, and then remained largely unchanged for millennia. Other inventions remained restricted to their regions of origin for very long time but, once diffused, underwent rapid improvement. The sickle and flail are in the first category, the iron moldboard plow and seed drill in the second. Tools and simple machines made field operations easier (thus providing a mechanical advantage) and faster, raised productivity, and enabled fewer people to grow more food, and the resulting energy surplus could be invested in structures and actions: without sickle and plow there would be no cathedrals—or no European voyages of discovery. I will first provide brief surveys of field operations, tools, and simple machines and then describe the dominance of cereal grains and the peculiarities of cropping cycles.

Field Work

A great deal of traditional farming required heavy work, but such spells were often followed by extended periods of less demanding activities or seasonal rest, an existential pattern quite different from the nearly constant high mobility of foraging. The shift from foraging to farming left a clear physical record in our bones. Examination of skeletal remains from nearly 2,000 individuals in Europe whose lives spanned 33,000 years, from the Upper Paleolithic to the twentieth century, revealed a decrease in the bending strength of leg bones as the population shifted to an increasingly sedentary lifestyle (Ruff et al. 2015). This process was complete by about two millennia ago, and there has been no further decline in leg bone strength since then, even as food production has become more mechanized, an observation confirming that the shift from foraging to farming, from mobility to sedentism, was a truly epochal divide in human evolution.

Environmental imperatives dictated the timing of field work in traditional farming, a requirement stressed in *De agri cultura*, the oldest extant compendium of farming advice, written by Marcus Cato during the second century BCE: "See that you carry out all farm operations betimes, for this is the way with farming: if you are late in doing one thing you will be late in doing everything." Seeding was done for millennia by hand, but all other field tasks required tools, whose assortment increased with time, and although there were some early designs of farm machines, such implements began to diffuse only during the early modern era (1500–1800).

Reviews of traditional farm tools, implements, and machines are available in books dealing with the history of agriculture in specific regions or countries that are cited later in this chapter, and in greater detail in more specialized volumes by White (1967) for the Roman world, Fussell (1952) and Morgan (1984) for Britain, Lerche (1994) for Denmark, Ardrey (1894) for the United States, and Bray (1984) for China. I have used all of these sources in describing all important implements and key cultivation practices and advances in the following pages; only animal harnesses will be dealt with in the section on traditional draft power.

In all of the Old World's high cultures the sequence started with plowing. In the words of a classic Chinese treatise, "No king or ruler of a state could dispense with it." Its indispensability is also reflected in ancient writing. Both the Sumerian cuneiform records and the Egyptian glyphs have pictograms for plows (Jensen 1969). Plowing prepares the ground for seeding much more thoroughly than hoeing: it breaks up the compacted soil, uproots weeds, and provides loosened, well-aerated ground in which seedlings can germinate and thrive. The first primitive scratch plows (ards), commonly used after 4000 BCE in Mesopotamia, were just pointed wooden sticks with a handle.

Later most of them were tipped with metal, but for centuries they remained symmetrical (depositing soil on both sides) and light. Such simple plows, which merely opened up a shallow furrow for seeds and left cut weeds on the surface, were the mainstay of both Greek and Roman farming (*aratrum* in Latin). They were used in large parts of the Middle East, Africa, and Asia until the twentieth century. In the poorest places they were, in extremis, pulled by people. Only in lighter, sandier soils would such an effort be speedier than hoeing (Bray 1984). The addition of a moldboard was by far the most important improvement. A moldboard guides the plowed-up soil to one side, turns it (partially or totally) over, buries the cut weeds, and cleans the furrow bottom for the next turn. A moldboard also makes it possible to till a field in one operation rather than by cross-plowing it, as required with ards. The first moldboards were just straight pieces of wood, but before the first century BCE the Han Chinese had introduced curved metal plates joined to the plowshare (fig. 3.1).

Heavy medieval European plows had a wooden moldboard and a coulter that cut an edge into the soil ahead of the wrought-iron share. During the second half of the eighteenth century Western plows still retained their heavy wooden wheels but carried well-curved iron moldboards (fig. 3.1). These moldboard plows became common in Europe and North America only with the availability of inexpensive steel, produced first by the Bessemer process during the 1860s, and soon afterward in much larger quantities in open-hearth furnaces (Smil 2016) (fig. 3.1). In most soils plowing leaves behind relatively large clods, which must be broken before seeding. Hoeing will work, but it is too slow and too laborious. That is why harrows have been used by all old plow cultures. Their development led from primitive brush harrows to a variety of wooden or metal frames to which were fastened wooden pegs or metal teeth or disks. Inverted harrows or rollers were often used to further smooth the surface.

After plowing, harrowing, and leveling, the ground was ready to be seeded. Although seed drills were used in Mesopotamia as early as 1300 BCE, and sowing plows were used by the Han Chinese, broadcast seeding by hand—wasteful and resulting in uneven germination—remained common in Europe until the nineteenth century. Simple drills that dropped

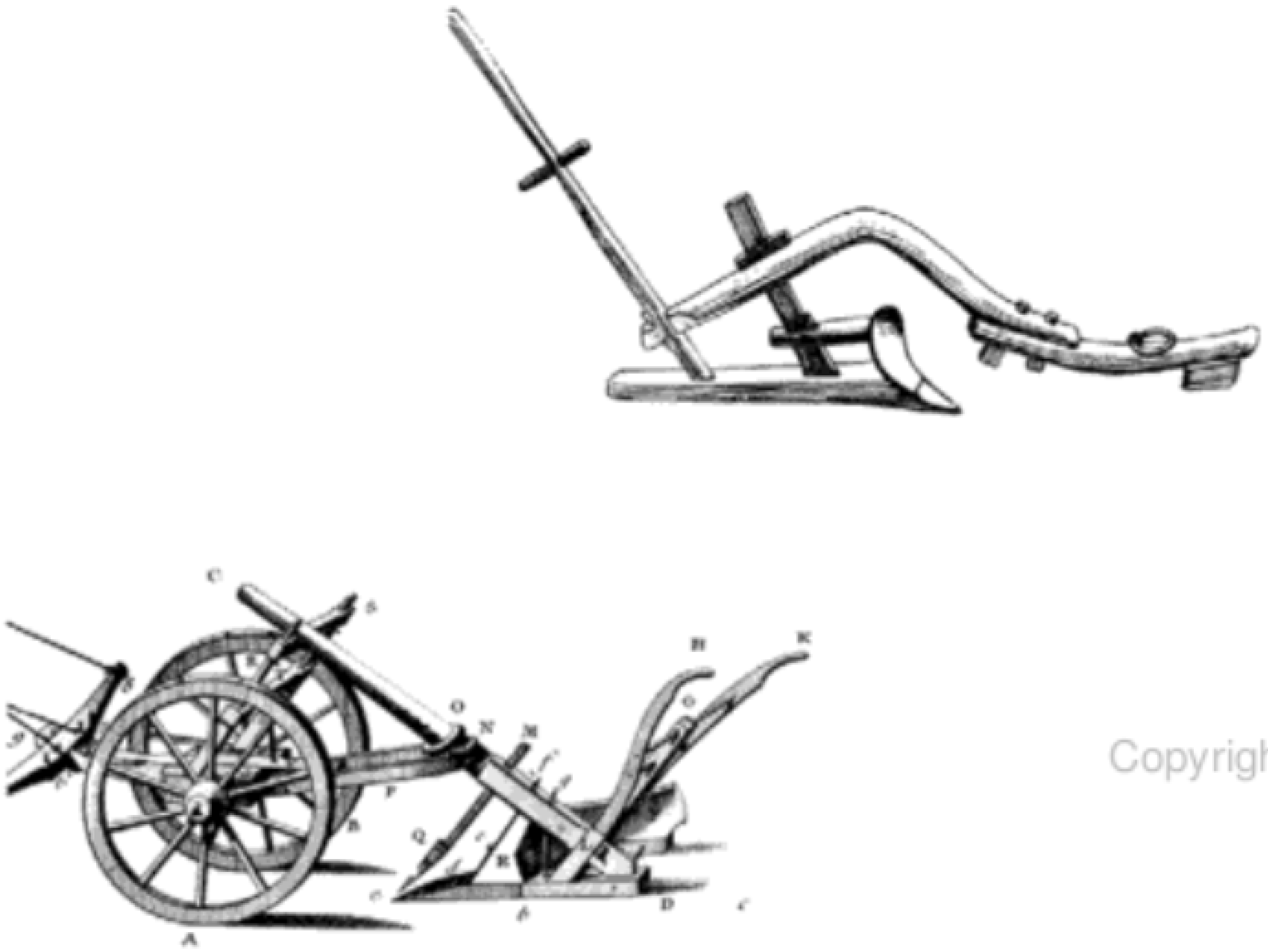

Figure 3.1
Evolution of curved moldboard plows. Traditional Chinese plow (top) had small but smoothly curving moldboard made from nonbrittle cast iron. Heavy European medieval plow, attached to a forecarriage (bottom left), had a pointed coulter in front of the share to cut the roots. The efficient American beam plow of the mid-nineteenth-century (bottom right) had its share and moldboard fused into a smoothly curving steel shape. *Sources:* Hopfen (1969), Diderot and D'Alembert (1769–1772) and Ardrey (1894).

seeds through a tube from a bin attached to a plow started to spread, first in northern Italy, during the late sixteenth century. Before long, many further innovations turned them into complex seeding machines. The intercultivation of growing crops was done largely by hoeing. Manures and other organic wastes were brought to fields on carts, in wooden cisterns, or in buckets carried at the end of shoulder beams, a common practice in East Asia. Then the wastes were pitchforked, poured, or ladled onto the field.

Sickles were the first harvesting tools to replace the short sharp stone cutters used by many foraging societies, and large scythes with cutting edges up to 1.5 m long are documented from Roman Gaul (Tresemer 1996; Fairlie 2011). Sickles have serrated (the oldest designs) or smooth edges and semicircular, straight, or slightly curved blades. Cutting with sickles was slow, and scythes, equipped with cradles for grain reaping, were preferred for harvesting larger areas (fig. 3.2). But sickle harvesting caused lower grain losses from ear shattering than broad sweeps with scythes, and the practice

Figure 3.2
Sickle and scythes pictured in the French *Encyclopédie* (Diderot and d'Alembert 1769–1772). The simple scythe on the right was used for grass mowing, the cradled one for cereal harvesting. Also shown are tools for hammering (straightening) and sharpening the scythes, as well as a rake and pitchforks. The bottom illustrations show nineteenth-century American grain harvesting by sickle and cradled scythe.

Box 3.1

Energy density and carbohydrate and protein content of principal grains

Cereal grains	Energy content (MJ/kg)	Carbohydrates (%)	Protein (%)
Wheat	13.5–13.9	70–75	9–13
Rice	14.8–15.0	76–78	7–8
Corn	14.7–14.8	73–75	9–10
Barley	13.8–14,2	73–75	9–11
Millet	13.5–13.9	72–75	9–10
Rye	13.3–13.9	72–75	9–11

Sources: Ranges compiled from USDA (2011) and Nutrition Value (2015).

cannot synthesize body proteins without consuming these essential amino acids in plant and animal foods.

All animal foods and all mushrooms supply perfect proteins (with adequate proportions of all nine essential amino acids), but all four leading staple grains (wheat, rice, corn, millet) and other important cereals (barley, oats, rye) are deficient in lysine, while tubers and most legumes are short of methionine and cysteine. Complete protein can be supplied even with the strictest vegetarian diets by combining foodstuffs with particular amino acid deficiencies. All traditional agricultural societies subsisting on largely vegetarian diets dominated by cereal grains have found independently (and obviously in the absence of any biochemical knowledge: amino acids and their role in nutrition were discovered only in the nineteenth century) a simple solution of this fundamental deficiency by including grains and legumes in mixed diets.

In China, soybeans (one of the few important food plants with complete protein), beans, peas, and peanuts have supplemented northern millets and wheat and southern rice. In India, protein from dal (a generic Hindi term for pulses, including lentils, peas, and chickpeas) has always enriched diets based on wheat and rice. In Europe the most common legume-cereal combinations relied on peas and beans and on wheat, barley, oats, and rye. In West Africa, peanuts and cowpeas were consumed alongside millets. And in the New World, corn and beans were not only eaten together in a variety of dishes, they were also commonly intercropped, grown together in alternating rows in the same field.

This means that even purely vegetarian diets could provide adequate protein intakes. At the same time, nearly all traditional societies valued meat highly, and where its consumption was proscribed they resorted either to dairy products (India) or fish (Japan) to consume high-quality animal protein. Two proteins in wheat are unique, not nutritionally but because of their physical (viscoelastic) properties. Monomeric gluten proteins (gliadin) are viscous; polymeric gluten proteins (glutenin) are elastic. When combined with water they form a gluten complex that is sufficiently elastic to allow a leavened dough to rise, yet strong enough to retain carbon dioxide bubbles formed during the yeast fermentation (Veraverbeke and Delcour 2002).

Without these wheat proteins there would be no leavened bread, the basic food of Western civilization. Yeast was never a problem: wild (naturally occurring) *Saccharomyces cerevisiae* is present on the skins of many fruits and berries, and many strains have been domesticated, resulting in changes in gene expressions and colony morphology (Kuthan et al. 2003). The dominance of cereals in traditional diets makes the energy balances of grain production the most revealing indicators of agricultural productivity. Data on typical agricultural labor requirements and their energy costs are available for a large variety of individual field and farmyard tasks (box 3.2).

But this level of detail is not necessary for calculating approximate energy balances. Using a representative average of typical net energy costs in traditional farming works quite well. The typical energy needs of moderate activities are about 4.5 times the basal metabolic rate for men, and five times for women, or 1 and 1.35 MJ/h (FAO 2004). Subtracting the respective basic existential needs results in net labor energy costs of 670 and 940 kJ/h. The simple mean is roughly 800 kJ/h, and I will use it as the net food energy cost of an average hour of labor in traditional agriculture. Similarly, gross grain output is calculated by multiplying the harvested mass by appropriate energy equivalents (typically by 15 GJ/t for grain with less than 15% moisture that can be stored).

The ratio of these two measures indicates the gross energy return, and hence the productivity, of these critical farming tasks. Net energy returns—after subtracting seed requirements and milling and storage losses—were substantially lower. Farmers had to set aside a portion of every harvest for the next year's seeding. The combination of low yields and high seed waste in hand broadcasting could mean that as much one-third or even one-half of medieval grain crops had to be set aside. With increasing harvests these shares fell gradually to less than 15%. Some grains are eaten whole, but

Box 3.2

Labor and energy requirements in traditional farming

Tasks	People/Animals	Hours per hectare	Energy cost
Hoeing			M–H
General	1/—	100–120	M–H
Wet soil	1/—	150–180	H
Plowing			M–H
Wooden plow	1/1	30–50	H
Wooden plow	1/2	20–30	H
Steel plow	1/2	10–15	M
Harrowing	1 /2	3–10	M
Sowing			L–M
Broadcasting	1/—	2–4	M
Seed drills	1/2	3–4	L
Weeding	1/—	150–300	M–H
Harvesting			M–H
Sickle (wheat)	1/—	30–55	H
Sickle (rice)	1/—	90–110	H
Cradle	1/—	8–25	H
Binding sheaves	1/—	8–12	M–H
Shocking	1/—	2–3	H
Reaper	1/2	1–3	M
Binder	1/3	1–2	M
Combine	4/20	2	M
Threshing			L–H
Treading	1/4	10–30	L
Flailing	1/—	30–100	H
Threshers	7/8	6–8	M

Notes: Light work (L) consumes less than 20 kJ of food energy per minute for an average adult man. Moderate (M) exertions range up to 30 kJ/min, and heavy (H) ones up to 40 kJ/min. Analogous rates for women are about 30% lower.

Sources: Ranges were compiled and calculated from data in Bailey (1908), Rogin (1931), Buck (1937), Shen (1951), and Esmay and Hall (1968). Energy cost indicators were estimated from metabolic studies reviewed in Durnin and Passmore (1967).

Box 3.3
Cereal milling

Whole grain flours incorporate the complete kernel, but white wheat flour is made only of the gain's endosperm (about 83% of total weight), with bran (about 14%) and germ (about 2.5%) separated for other uses (Wheat Foods Council 2015). The production of white rice entails even higher milling loss. The husk layer makes up 20% of rice grain mass; its removal produces brown rice. The bran layer makes up 8–10% of the grain, and different degrees of its removal produce more or less polished (white) rice that contains only 70–72% of the grain's initial weight (IRRI 2015).

Japanese testimonies of food shortages refer to people forced to eat brown rice, and when matters got worse brown rice mixed with barley, and ultimately just barley (Smil and Kobayashi 2011). Corn milling removes the tip cap, bran coat, and germ, leaving the endosperm, about 83% of the kernel. Corn flour for making tortillas and tamales, *masa harina,* is produced by nixtamalization, or the wet milling of kernels soaked in lime solution (Sierra-Macías et al. 2010; Feast and Phrase 2015). This loosens the hulls from the kernels, softens the kernels by dissolving hemicellulose, reduces the presence of mycotoxins, and enhances the bioavailability of niacin (vitamin B_3).

before actual food preparation (cooking or baking) most cereals are milled first, and in the process lose a significant share of the whole grain's mass (box 3.3).

Storage losses on traditional farms—to fungi and insect infestations and to rodents able to access bins or jars—would commonly reduce the edible grain total by anywhere between a few percent to more than 10%. As already noted, grain with less than 15% moisture can be stored for long periods of time; higher moistures, especially when combined with higher temperatures, provide perfect conditions for seed germination and for the growth of insects and fungi. In addition, improperly stored grain can be consumed by rodents. Even as recently as the mid-eighteenth century a combination of seeding requirements and storage losses could have reduced the gross energy gain of European grains by around 25%.

Cropping Cycles

The commonalities of annual crop cycles and the dominance of cereal cultivation obscured an astonishing variety of local and regional peculiarities. Some of them were of distinctly cultural origins, but most developed as responses and adaptations to different environments. Most notably, environmental conditions determined the choice of leading crops, and hence the makeup of typical diets. They also molded the rhythm of annual farming cycles, which determined the management of agricultural labor. Wheat was able to spread from the Middle East to all continents because it does well in many climates (in semideserts as well as in rainy temperate zones, and it is the leading food cultivar in the temperate zone between 30 and 60°N) and elevations (from sea level to as high as 3,000 m above sea level) and on many soils, as long as they are well drained (Heyne 1987; Sharma 2012).

In contrast, rice is originally a semiaquatic plant of tropical lowlands and grows in fields flooded with water until just before the harvest (Smith and Anilkumar 2012). Its cultivation has also spread far beyond the original South Asian core, but the best yields have always been in rainy tropical and subtropical regions (Mak 2010). Constructing and maintaining ridged wet fields, germinating seeds in nurseries, transplanting seedlings, and providing subsidiary irrigation add up to much higher labor requirements than for wheat cultivation. Unlike wheat, corn yields best harvests in regions with warm and rainy growing seasons, but it, too, prefers well-drained soils (Sprague and Dudley 1988). Potatoes grow best where summers are cool and rains abundant.

Annual farming cycles were governed by water availability in both arid subtropics and in monsoonal regions, and by the length of growing seasons in temperate climate. In Egypt the Nile's floods determined the annual cycle of cultivation until the adoption of widespread perennial irrigation in the second half of the nineteenth century. Sowing began as soon as the water receded (usually in November), and no field work could be done between the end of June, when the waters started to rise, and the end of October, when they rapidly receded, with harvests 150–185 days later (Hassan 1984; Janick 2002). This pattern prevailed largely unchanged until the nineteenth century.

In monsoonal Asia, rice cultivation had to rely on summer precipitation, usually abundant but often delayed. For example, in intensive Chinese cropping, seedlings of early rice were transplanted from nurseries to fields in April. The first crop's harvest in July was followed immediately by the transplanting of the late rice, which was harvested in the late fall and, in turn, followed by a winter crop. Double-cropping in temperate zones worked under much less pressure. In Western Europe the overwintering crops planted in the fall were harvested five to seven months later. They were followed by spring-seeded crops, which matured in four to five months. In cold northern regions the ground would thaw by April but the

Draft Animals

Domestication has resulted in many working breeds with distinctive characteristics, with weights spanning an order of magnitude, from just over 100 kg for small donkeys to just over 1,000 kg for the heaviest draft horses. Indian bullocks weighed less than 400 kg; Italian Romagnola or Chianina cattle were easily twice as heavy (Bartosiewicz et al. 1997; Lenstra and Bradley 1999). Most horses in Asia and parts of Europe were just ponies, less than 14 hands tall and weighing no more than an Asian ox. A hand, a traditional English measure, is four inches (10.16 cm), and the animal's height was measured from the ground to its withers, the ridge between the shoulder blades below its neck and head. Roman horses were 11–13 hands. The heaviest European breeds of the early modern era—Belgian Brabançons, French Boulonnais and Percherons, Scottish Clydesdales, English Suffolks and Shires, German Rheinlanders, Russia's Heavy Draft—approached and even topped 17 hands and weighed close to, or even just above, 1,000 kg (Silver 1976; Oklahoma State University 2015). Water buffaloes can range from just 250 kg to 700 kg (Cockrill 1974; Borghese 2005).

Traditional agricultures used animals for a variety of field and farmyard tasks, but plowing was undoubtedly the activity where they made the greatest difference (Leser 1931). In general, the tractive force of working animals is roughly proportional to their weight, and other variables determining their actual performance include the animal's sex, age, health, and experience, the efficiency of the harness, and soil and terrain conditions. As all of these variables can vary rather widely, it is preferable to summarize the useful power of common working species in terms of typical ranges (Hopfen 1969; Cockrill 1974; Goe and Dowell 1980). A typical draft is 15% of animal's body weight but for horses it is up to 35% during brief exertions (about 2 kW) and even more during a few seconds of supreme effort (Collins and Caine 1926). The combination of large mass and relatively high speed makes horses the best draft animals, but most horses could not work steadily at the rate of one horsepower (745 W), and usually delivered between 500 and 850 W (box 3.4, fig. 3.3).

Actual draft requirements varied widely with the task (the extremes of heavy and light work might be deep plowing and harrowing) and with soil type (demanding in heavy clay soils, much easier in sandy soils). Shallow plowing (with a single plowshare) and grass mowing needed a sustained draft of 80–120 kg, deep plowing required drafts of 120–170 kg, and a 200-kg pull was needed for a mechanical grain reaper and binder. Even an average horse pair can do all of these tasks, but a pair of oxen was inadequate

Box 3.4

Typical weights, drafts, working speeds, and power of domestic animals

Animals	Weights (kg) Common range	 Large sizes	Typical draft (kg)	Usual speed (m/s)	Power (W)
Horses	350–700	800–1000	50–80	0.9–1.1	500–850
Mules	350–500	500–600	50–60	0.9–1.0	500–600
Oxen	350–700	800–950	40–70	0.6–0.8	250–550
Cows	200–400	500–600	20–40	0.6–0.7	100–300
Buffaloes	300–600	600–700	30–60	0.8–0.9	250–550
Donkeys	200–300	300–350	15–30	0.6–0.7	100–200

Note: Power values are rounded to the nearest 50 W.

Sources: Based on Hopfen (1969), Rouse (1970), Cockrill (1974), and Goe and Dowell (1980).

for deep plowing or harvesting with a reaper. At the same time, mechanical imperatives favored smaller animals: everything else being equal, their line of pull is more parallel to the direction of traction, resulting in higher efficiency, and in plowing, a lower pull line also reduces the uplift on the plow, making it easier for a plowman to guide it. Lighter animals are also often more agile, and they may compensate for their lower weight with tenacity and endurance.

Draft potential could be translated into effective performance only with practical harnesses (Lefebvre des Noëttes 1924; Haudricourt and Delamarre 1955; Needham 1965; Spruytte 1983; Weller 1999; Gans 2004). Traction must be transferred to the point of work—whether plowshare or reaper's edge—by a gear that allows its efficient transmission and also enables human control of the animal's movements. Such designs may look simple, but they took a long time to emerge. Cattle, the first working animals, were harnessed by yokes, straight or curved wooden bars fastened to the animal's horns or neck.

The oldest Mesopotamian harness (best used with strong, short-necked animals, and later common in Spain and Latin America) was the double head yoke, fixed either at the front or the back of the head (fig. 3.4). That was a primitive harness: merely a long wooden beam whose throat fastenings may choke the animal in heavier labor and whose traction angle is too large. Moreover, to avoid excessive choking of one ox or cow, the animals

Figure 3.3
Comparisons of animal draft power showing the clear superiority of horses. Plotted from data in Hopfen (1969), Rouse (1970), and Cockrill (1974).

must be of identical height, and a pair must be harnessed even when a single animal would do for lighter work. A more comfortable single head yoke was used in several parts of Europe (the eastern Baltic region, southwestern Germany). The single neck yoke, connected to two shafts or to traces and a swingletree, was common throughout East Asia, and also in Central Europe (fig. 3.4). Africa, the Middle East, and South Asia favored a double neck yoke.

Horses are the most powerful draft animals. Unlike cattle, whose body mass is almost equally divided between the front and the rear, horses' fronts

Figure 3.4
The head yoke was the first, and rather inefficient, harness for working oxen. The neck yoke became the dominant way of harnessing cattle throughout the Old World. Adapted from Hopfen (1963) and from a late Ming dynasty (1637) illustration.

are notably heavier than their rears (ratio of about 3:2), and so the pulling animal can take a better advantage of inertial motion than cattle (Smythe 1967). Except in heavy, wet soils, horses can work in fields steadily at speeds of around 1 m/s, easily 30–50% faster than oxen. Maximum two-hour pulls for paired heavy horses can be almost twice as high as for the best cattle pairs. The largest horses can thus work for short spells at rates surpassing 2 kW, or more than three standard horsepower. But humpback cattle are superior in the tropics thanks to their efficient heat regulation; they are also less susceptible to tick infestation. And water buffaloes thrive in wet tropics and convert roughage feed more efficiently than cattle and can graze on aquatic plants while fully submerged.

The oldest existing images of working horses do not show them laboring in fields but rather pulling light ceremonial or attack carriages. During most of antiquity, draft horses were harnessed by a dorsal yoke (Weller 1999). The dorsal yoke was a forked device, wooden or metal, that was placed on the animal directly behind its withers and held in place by a chest strap that ran across the animal's breast and was fastened on both sides of the yoke and by a surcingle (a strap running over the back and under the belly). Inaccurate reconstruction of the Roman harness by Lefebvre des Noëttes (1924) led to a mistaken but for decades a widely accepted conclusion that this was a very inefficient arrangement because it choked the animal, as the breast collar tended to ride up (box 3.5).

The breastband harness, introduced in China no later than the early Han dynasty, had its point of traction too far away from the animal's most powerful pectoral muscles (fig. 3.5). Nonetheless, the design spread across Eurasia, reaching Italy as early as the fifth century, most likely with migrating Ostrogoths, and northern Europe some 300 years later. But it took another Chinese invention to turn horses into superior working animals. The collar harness was first used in China perhaps as early as the first century BCE as a soft support for the hard yoke; only gradually was it transformed into a single component. By the fifth century CE its simple variant can be seen on the Donghuang frescoes. Philological evidence suggests that by the ninth century it had reached Europe, where it was in general use within about three centuries, and the design remained largely unchanged until horses were replaced by machines more than 700 years later. It is still used on a diminishing number of China's working horses.

The standard collar harness consists of a single oval wooden (later also metal) frame (hame), lined for a comfortable fit onto horse's shoulders, often with a separate collar pad underneath. Draft traces are connected to the hame just above the horse's shoulder blades (fig. 3.6). The horse's

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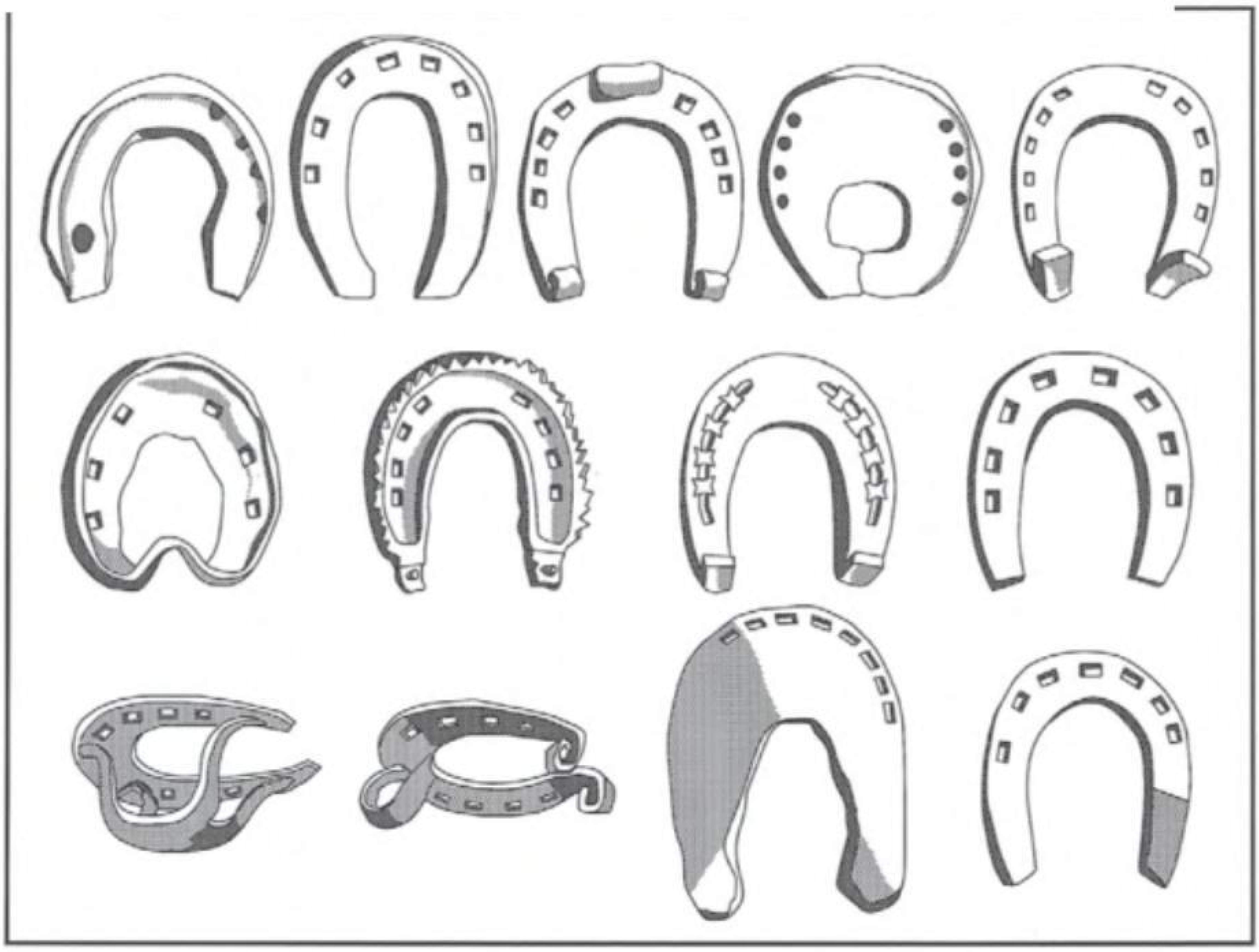

Figure 3.6

Components of a typical late nineteenth-century collar harness (based on Telleen 1977 and Villiers 1976)—and a variety of mid-eighteenth-century horseshoes (Diderot and d'Alembert 1769–1772). The shapes (starting on the left) are, respectively, typical English, Spanish, German, Turkish, and French horseshoes.

the animals to rest, even to doze, while standing, with hardly any metabolic cost, and to spend little energy while grazing (Smythe 1967). All other mammals need about 10% more energy when standing as compared to lying down.

Even smaller and poorly harnessed animals made a great difference (Esmay and Hall 1968; Rogin 1931; Slicher van Bath 1963). A peasant working with a hoe would need at least 100 hours, and in heavy soils up to 200 hours, to prepare a hectare of land for planting cereals. Even with a simple ox-drawn wooden plow that task could be done in just over 30 hours. Hoe-dependent farming could never have attained the scale of cultivation made possible by animal-drawn plowing. Besides speeding up plowing and harvesting, animal labor also made it possible to lift large volumes of irrigation water from deeper wells. Animals were used to operate such food-processing machines as mills, grinders, and presses at rates far surpassing human capabilities. Relief from long hours of tiresome labor was no less important than the higher output rates, but more animal work required more cultivated land to grow feed crops. This was easily done in North America and in parts of Europe, where the upkeep of horses at times claimed up to one-third of all agricultural area.

Not surprisingly, in China and other densely populated Asian nations, cattle were the preferred draft animals. Being ruminants, they could be maintained solely on roughage from straw and from grazing. And when working they do not have to be fed much grain either: concentrate feed can come largely from such crop-processing residues as brans and oil cakes. I estimated that in China's traditional farming the cultivation of feed for draft animals claimed only about 5% of the annually harvested area. In India, fodder crops also accounted traditionally for about 5% of all cultivated land but most of this feed went to milking animals, and some of it ended up nourishing sacred cows (Harris 1966; Heston 1971). Feed for the working bullocks probably claimed less than 3% of all farmland. In the most densely populated parts of the Indian subcontinent cattle survived on a combination of roadside and canal-bank grazing and on the feeding of crop by-products, ranging from rice straw and mustard oil cakes to chopped banana leaves (Odend'hal 1972).

Indian or Chinese draft animals were clear energetic bargains. Many of them did not compete for crop harvests with people at all, while some preempted at most an area of cultivated land, which would grow food for one person a year. But their useful annual labor was the equivalent of three to five peasants working 300 days a year. An average nineteenth-century European or American horse could not give such a high relative return, but