CHAPTER 1

# *1850s: Solar Society*

> The energy of the universe is constant.
>
> Rudolf Clausius, *The Mechanical Theory of Heat,* 1867

From the small villages that domesticated maize, beans, and squash some 7,000 years ago, to the Aztec empire of 1500, to the colonial possession that declared independence from the Spanish crown in 1821, the region we now call Mexico has sustained many human societies. Some lived off hunting and the collection of plants, nuts, and roots for centuries, perhaps millennia, and continued doing so into the mid-nineteenth century. Others built large cities featuring massive structures and long, straight thoroughfares. A few organized some of the world's first capitalist economies, mining vast amounts of silver that shaped global trade. The majority organized themselves in small rural communities that cultivated maize, beans, and squash, the trinity of Mesoamerican staples. But regardless of when, where, or how these societies lived, all subsisted within the energy constraints of the sun's cycles and rhythms – the solar energy regime. Such was the case for every human society until the emergence of coal as the basis of eighteenth-century British life.

Like their predecessors, the diverse populations that made up Mexican society in the mid-nineteenth century depended on the flow of light energy from the sun to produce food to feed animals and humans – the sources of all labor and transport. Sunlight set the hydrological cycle that regulated running water for irrigation and waterwheels. Life in 1850s Mexico was characterized by almost complete dependence on local environmental conditions. Even in the richest ecosystems, energy was scarce, so growth was exceptional and reduced to brief spurts.[1] The prohibitive energetics of

[1] Historians tend to project rapid economic growth – characteristic of industrial societies often considered "natural" – backwards into the past, asking why growth didn't happen in past societies, instead of asking why growth happened at all. See E. A. Wrigley, *Energy and the English Industrial Revolution* (Cambridge: Cambridge University Press, 2010), chapter 1.

transportation meant that little more than luxury items or low-bulk valuable items like silver could be carried overland beyond a few dozen kilometers. Overusing any given local resource faced relatively quick penalization. Overexploitation of forests for the increased production of iron could only be sustained for a short period before wood scarcity set in. By land, wood could only be transported over 30 or so kilometers before costs became exorbitant (with the exception of all-important fuelwood, for which mines often paid handsomely). Even if forests were abundant beyond that boundary, communities still experienced wood scarcity.

But things were beginning to change. The limits of the old energy regime were expanding through a combination of increased waterpower and the introduction of steam power. Until the advent of the steam engine in eighteenth-century Britain, the only way humans could put to work the solar energy stored in plants was through biological converters (animals and people). When Mexico's mining companies and factories introduced steam power to their operations, wood became a fuel to generate work for the first time.[2] Nevertheless, the mid-nineteenth century marks a transitional moment in Mexican history. If we were to take a snapshot of this moment, the constraints of the solar energy regime still shaped every aspect of society. Yet new ways of extracting and transforming energy were spreading, setting in motion a series of developments that would transform Mexican society over the following decades. During the 1850s, Mexico existed on the boundary between two ages.

To understand this critical moment, the chapter presents a panoramic view of mid-nineteenth-century Mexico. It emphasizes the material and environmental conditions across the country, paying particular attention to energy use. The chapter analyzes the relationship between economic and political institutions, cultural practices, and the country's solar energy regime. Through this snapshot, the chapter seeks to sketch the basic contours of Mexico's pre–fossil fuel era, providing a baseline against which the energy, social, economic, and environmental changes and continuities examined in subsequent chapters can be easily assessed.

## The Basics

Before turning to our story, however, a word on key concepts used throughout this chapter. The notion of energy is frequently discussed

[2] That said, steam engines were scarcely employed in the 1850s, which limited their impact on production.

throughout this chapter – indeed, throughout this entire book. What is energy exactly? It is best thought of as a flow. Through thermonuclear reactions, the sun radiates thermal energy that plants (autotrophs or primary converters) transform into chemical energy, building the basis of most life processes on our planet.[3] Other organisms such as animals (heterotrophs or secondary converters) consume plants or other animals and transform chemical energy into life-sustaining heat. A small percentage of this energy is converted into mechanical energy, or work. Solar radiation also drives the hydrological cycle of evaporation, condensation, precipitation, and runoff. The sun heats surface ocean water until it evaporates, rising into the atmosphere as water vapor. At certain heights, the moist air cools and loses its capacity to retain water vapor, which initiates the condensation process. Clouds form and are transported by wind currents around the globe, where they return water to the surface as precipitation. Water on the ground can either return to the atmosphere as transpiration, empty as runoff into lakes, rivers, and oceans, or seep into the earth as groundwater. Finally, the sun's uneven heating of the earth causes air to move, creating wind. During daytime, the air heats faster over land than over water. Warm air expands and rises, leaving cooler ocean air rushing inland in its place. At night, this process reverses, as air over land cools faster. Chemical energy, the hydrological cycle, and wind currents were all components of the solar energy regime under which Mexican society operated well into the nineteenth century.

Another important aspect of solar radiation is what ecologists call the net primary productivity of ecosystems.[4] Every organism uses energy to grow and reproduce. Plants, the basis of both terrestrial and maritime ecosystems, use energy in biomass production, growth, and reproduction. They capture a mere 0.1 percent of light that reaches the earth, converting it into plant tissue and chemical energy.[5] The net primary productivity (NPP) is the energy that remains after these processes and is stored as organic matter. NPP in Mexico is highly variable, but it averages 3 tons per hectare

[3] Thermonuclear reactions at the sun's core fuse hydrogen atoms into heavier helium atoms, releasing lost mass into space as radiant energy. On general energetics, see Howard T. Odum and Elisabeth C. Odum, *Energy Basis for Man and Nature* (New York: McGraw-Hill, 1976).

[4] David Pimentel and Marcia H. Pimentel, *Food, Energy, and Society* (Boca Raton: CRC Press, 2007), 4–20.

[5] Solar irradiation varies globally. Mexico receives a daily average of 5 $kWh/m^2$, double that of Germany and similar to some regions in Africa, the Andes, and Oceania. Within Mexico, the arid northwest has the highest solar insolation, while the central highlands and the tropical lowlands of the southeast receive less. See Sergio Romero, et al., "Energy in Mexico: Policy and Technologies for a Sustainable Future" (México, D. F.: USAID; Wilson Center, Mexico institute; ITAM, 2013).

annually. Given the country's total territory of 197,255,000 hectares, Mexico's entire vegetative cover produces some 591,765,000 tons annually. Assuming 4,200 kcal per kg of biomass, all of Mexico's ecosystems thus produce 2,485,413,000,000,000 kcal per year. This *annual energy flow* represented the theoretical limit of energy available to mid-nineteenth-century Mexican society.

Of course, human beings had to share this flow with countless other animals and could tap into only a fraction of it. Agriculture represented the basic way to appropriate some of this flow. Like every other farming system around the world, mid-nineteenth-century Mexican agriculture sought to control and harvest as much incoming solar energy as possible for human needs. It concentrated solar energy in crops to sustain human and animal labor, which performed a wide variety of tasks: making shoes in small workshops; extracting ore from deep shafts in industrial-scale mining operations; and building towns and cities and the roads connecting them.

All of these basic processes lay at the heart of Mexico's mid-nineteenth-century energy system. Scholars refer to this energy system as the solar energy regime, the biological *ancién regime*, the somatic energy regime, or the organic energy regime. All four terms are useful but emphasize different aspects of energy use. The terms "biological" and "organic" underline the importance of organic components like plants and animals for the societies that depended on them. That said, they implicitly suggest that the fossil fuel energy regime under which we currently live is not organic. This is misleading: both coal and oil derive from fossilized vegetable matter,[6] which is organic. The term "somatic" draws attention to human and animal muscle's capacity to do work but overlooks the importance of hydraulic and eolic (wind) power to some societies living under this regime. The term "solar" avoids both problems and reminds the reader of the non–fossil fuel basis of these societies.[7] As such, I will use the concept of "solar energy regime" moving forward.[8]

Mexico's solar energy system had specific ecological and technological characteristics. By far the most important energy source was food, a form of

[6] Oil is also derived from zooplankton.

[7] Of course, all energy sources, including fossil fuels, ultimately derive from sunlight.

[8] Edmund Burke III, "The Big Story: Human History, Energy Regimes, and the Environment," in *The Environment and World History* (Berkeley: University of California Press, 2009), 33–53; John R. McNeill, *Something New under the Sun: An Environmental History of the Twentieth-Century World* (New York: W.W. Norton & Company, 2001); Rolf Peter Sieferle, *The Subterranean Forest*: Energy Systems and the Industrial Revolution (Cambridge: The White Horse Press, 2001); Vaclav Smil, Energy in World History. Essays in World History (Boulder: Westview Press, 1994); Wrigley, *Energy and the English Industrial Revolution*.

https://doi.org/10.1017/9781108923972.002 Published online by Cambridge University Press

chemical energy that humans and animals converted and transformed into Mexico's main source of mechanical power: muscle. Another source of energy was water, transformed by nonbiological converters like the waterwheel into mechanical energy that moved mills, spindles, and so on. Wind went to work at sea, moving sail ships along Mexico's coasts. Wood was the main source of heat energy, although dung and cornstalks substituted in some wood-scarce regions.[9] A small number of steam engines burned wood and small amounts of imported coal in mines and textile factories (and one or two ships), but they represented a marginal percentage of Mexico's overall energy output.

## The Longer History

Mexico's history, of course, did not begin in 1850. Timeframes and periodizations are contested historical constructs. Still, historians have to start their stories somewhere. While this chapter offers a snapshot of the country in the mid-nineteenth century, this picture must be historically contextualized to avoid misleading. A succinct overview of the fundamental ecological transformations that marked New Spain after 1500 and Mexico before 1850 will ensure that.

In the early sixteenth century, what is today Mexico encompassed three distinct regions: the north populated by hunter-gatherers and a few cultivators; the tropical lowlands dominated by slash-and-burn farmers; and the Mesoamerican highlands with a maize-based civilization of family producers and large polities. While all indigenous societies shaped their environments, the latter inhabited a "sculptured landscape," none more so than in the Valley of Mexico, where there were large urban centers with whitewashed walls like Texcoco. The surrounding countryside was dotted with villages and heavily cultivated with maize fields (*milpas*), some of them flanked by rows of maguey plants to protect from wind and soil erosion. In the middle were five interconnected lakes. The two lakes furthest north (Zumpango and Xaltocan) and the two in the south (Chalco and Xochimilco) were freshwater lakes located at a slightly higher elevation that drained into the saline waters of Lake Texcoco. Crisscrossing the lakes, a series of structures both connected and divided them. There were dikes that regulated the water level of the lakes and prevented flooding as well as keeping Lake Texcoco's more

[9] William W. Carpenter, *Travels and Adventures in Mexico: In the Course of Journeys of Upward of 2500 Miles, Performed on Foot; Giving an Account of the Manners and Customs of the People, and the Agricultural and Mineral Resources of That Country* (New York: Harper & Brothers, Publishers, 1851), 147.

saline eastern waters from mixing with its less brackish western waters, known as the lake of Mexico. There were also long, wide causeways linking all the main population centers with the largest urban conglomeration in the valley, Tenochtitlan. Located on an artificially expanded island on the western fringe of Lake Texcoco with a population of about 200,000, Tenochtitlan was one of the largest cities in the world. The valley in which it sat was one of the most humanized landscapes in the Americas. It had been so for centuries, if not millennia.[10]

European arrival initiated a process of incalculable consequences for the whole of the western hemisphere: the Columbian Exchange. Two halves of the world separated since the land bridge of Beringia that had been submerged by the North Pacific sometime in the tenth millennium BCE came together on October 12, 1492. The exchange was an unequal affair. The influx of organisms from east to west was far larger than that from west to east, with Europeans bringing domesticated animals (horses, cattle, goats, pigs, and sheep), plants (wheat, rye, barley, oranges, sugarcane, and coffee, among others), and, most ominously, pathogens (smallpox, influenza, chickenpox, measles, and whooping cough). The flow from west to east included maize, potatoes, tomatoes, beans, squash, tobacco, peanuts, cassava, pineapple, peppers, and cotton. American plants would change the world, but among the animals domesticated in the Americas, only the turkey became important elsewhere.[11]

Eurasian animal domesticates had no equivalent in the Americas. Although key species for the trajectory of human history such as horses and camels originally evolved in the Americas, they became extinct by the end of the last Ice Age, around 11,000 BC, along with some 70 percent of all large mammals. This megafauna extinction likely resulted from human predation and climate change. When these large animals disappeared, the indigenous population lost a number of potential domesticates, with important long-term consequences for different aspects of their civilizations, including the dominance of human muscle, food production, and warfare.[12]

[10] The term "sculptured landscape" comes from T. M. Whitmore and B.L. Turner, *Cultivated Landscapes of Middle America on the Eve of Conquest* (Oxford; New York: Oxford University Press, 2001), 2. A masterful description of the Valley of Mexico during early Spanish rule is Charles Gibson, *The Aztecs under Spanish Rule; a History of the Indians of the Valley of Mexico, 1519–1810* (Stanford: Stanford University Press, 1964), chapter 1.

[11] The key work on the Columbian Exchange is, of course, Alfred Crosby, *The Columbian Exchange: Biological and Cultural Consequences of 1492* (Westport: Greenwood Press, 1972).

[12] See Paul S. Martin, "Pleistocene Overkill," *Natural History* 76, no. 10 (1967): 32–8. On the consequences of the megafauna extinctions for the indigenous population of the Americas, see Jared M. Diamond's controversial work *Guns, Germs, and Steel: The Fates of Human Societies*

While, early on, domesticated animals numbered no more than a few horses, cattle, pigs, sheep, and goats, within decades their populations exploded into thousands of semi-feral roaming animals. It has been argued that Spaniards prevented animal populations, sheep in particular, from reestablishing a sustainable population in parts of central Mexico after their numbers crashed by artificially overstocking the region. This led to permanent degradation of landscapes, like those of the Valle del Mezquital, which was transformed within a century from a rich agricultural land into an impoverished and arid region of scrub vegetation. Other scholars have criticized this analysis for using a single factor (overgrazing) to explain a highly complex process like land degradation. There is evidence, too, that suggests Spaniards were aware of the danger of overgrazing and took steps to mitigate it, particularly through transhumance. Terrace abandonment due to native demographic collapse has also been signaled as an important cause behind massive soil erosion in places like the Valle del Mezquital. Climate change, specifically the relatively cool and dry period known as the Little Ice Age (roughly from 1400 to 1800), may have played an important role in the environmental changes attributed to the "plague" of sheep. In any case, there is little doubt that the introduction of livestock into the Americas and into what is today Mexico deeply shaped the landscape.[13]

While the prehistoric extinction of the megafauna and the sixteenth-century introduction of Eurasian domesticates had great environmental impacts on the Americas, the arrival of Europeans and their diseases caused perhaps the largest demographic collapse in recorded history. Wave after wave of epidemic outbreaks of smallpox, measles, mumps, influenza, and other diseases decimated native populations, whose almost complete isolation from the Old World for millennia left them without immunity and highly vulnerable to these diseases. Moreover, most human diseases were of

(New York: W.W. Norton & Co., 1998), part 1. An important exception to megafauna extinctions across the Americas is the camelids of South America; the llama and the alpaca became important domesticates in pre-Columbian Andean civilizations.

[13] On the impact of livestock in central Mexico, see Elinor G. K. Melville, *A Plague of Sheep: Environmental Consequences of the Conquest of Mexico* (Cambridge: Cambridge University Press, 1994). For an opposing view, see Karl W. Butzer and Elisabeth K. Butzer, "The Natural Vegetation of the Mexican Bajio: Archival Documentation of a 16th-Century Savanna Environment," *Quaternary International* 43144 (1997): 161–72. For a detailed review of the Melville–Butzer debate, see Richard William Hunter, *People, Sheep, and Landscape Change in Colonial Mexico the Sixteenth-Century Transformation of the Valle del Mezquital* (Baton Rouge: Louisiana State University, 2009), chapter 1. A colonial account of the demographic explosion among introduced herbivores is José de Acosta, *Historia natural y moral de las Indias, en que se tratan de las cosas notables del cielo, y elementos, metales, plantas y animales dellas: y los ritos, y ceremonias, leyes y gobierno, y guerras de los indios* (México: Fondo de Cultura Económica, 1962), libro 4, capítulo XXXIII.

zoonotic origin (animal-borne), derived from the close contact between humans and domesticated animals. Native Americans arrived in the Americas before any large animal had been domesticated, with the exception of the dog, and thus received little exposure to zoonotic diseases prior to the Columbian Exchange. In addition, the ancestors of the indigenous populations had crossed Beringia when climatic conditions were very cold, which killed off most pathogens. In all, between 1492 and 1650 perhaps as many as 90 percent of the indigenous population in parts of the New World succumbed to disease. For example, the population of the Basin of Mexico – which included the valley of the same name plus adjacent areas – declined from 1–1.2 million in 1519 to only about 100,000 people in 1650. Only in the twentieth century did the local human population again reach the one-million watermark.[14]

Human depopulation changed everything. In a society overwhelmingly dependent on human labor, muscle power became scarce. A rapidly declining indigenous population in the tropical lowlands was replaced by enslaved Africans. In the Mesoamerican highlands, Spanish authorities concentrated, with the mediation of local elites, the remaining indigenous population in landed republics. Dwindling numbers made it impossible to maintain large infrastructure works like the complex hydraulic system in the lakes of the Valley of Mexico, leading to recurrent flooding and centuries-long drainage projects. Labor-intensive *chinampas* declined in number and area. On the other hand, demographic collapse made land plentiful. Radical changes ensued. Villages became self-sufficient and enjoyed a large degree of political and cultural autonomy, although many partook in the commercial economy as seasonal laborers for cash wages (necessary for maintaining ritual life and paying taxes). Old World fruits and livestock increased the chemical energy at their disposal. Provisioned by large estates devoted to commercial crops like wheat, urban centers became manufacturing and financial centers and seats of political and judicial power mediating social conflict. Native and mixed-race migrants, vast herds of livestock (cattle, sheep, and horses), and some

[14] A classic analysis of indigenous demographic collapse in central Mexico is Sherburne Friend Cook and Woodrow Wilson Borah, *The Indian Population of Central Mexico, 1531–1610* (Berkeley: University of California Press, 1960). See also Rebecca Storey, "Population Decline during and after Conquest," in Deborah L. Nichols, ed., *The Oxford Handbook of Mesoamerican Archaeology* (Oxford; New York: Oxford University Press, 2012). By comparison, one of the other great demographic cataclysms in human history, the Black Plague, had an average mortality rate of "only" around 50 percent. See John Aberth, *The Black Death: The Great Mortality of 1348–1350: A Brief History with Documents* (Bedford/St. Martin's: Palgrave Macmillan, 2005), 3.

Europeans pushed the frontier north of Mesoamerica into the vast arid plateau.[15]

These newcomers built a highly commercialized economy organized around the extraction and export of silver in the Bajío and the far north. Chinese demand and an emerging global trade increasingly dominated by Europeans drove silver mining across this vast region. Urban centers like Querétaro provided mines with textiles and manufactures crafted in their many *obrajes*, workshops, and, in the eighteenth century, huge factories (tobacco, for example). Cash wages were the norm. Large haciendas and ranchos supplied the silver economy with leather products, tallow, fuelwood, and animals as muscle power to move complex machinery and winches. It was one of the earliest capitalist societies anywhere, whose main product, silver, profoundly influenced the early modern world.[16]

By 1800, these two core areas of New Spain, the central highlands and the Bajío-North, were among the richest in the Americas. They were also highly urbanized and featured several important cities, including Mexico City. The largest in the western hemisphere at the time, Mexico City was the financial and trade center linking the north's mining economy with the world of relatively autonomous peasant communities, commercial estates, and *chinampa* agriculture in the central highlands. Sustained by the enormous flow of silver and connected to global circuits of trade, this urban, commercial world came crashing down in the second decade of the nineteenth century when an explosive mix of population growth, overexploitation, and a political vacuum created by Napoleon's invasion of Spain erupted in a devastating war and popular insurgency. The country became independent in 1821.[17]

The postindependence decades saw a number of conflictive changes. Silver production fell by half and only began to recover in the 1840s.[18] The commercial economy suffered, especially mines and large estates, but not communities that depended mostly on subsistence farming, which enjoyed renewed autonomy and abundant harvests.[19] Exports and trade declined,

[15] This analysis is based on personal communication with John Tutino. For a detailed account of the changes described here, see John Tutino, *The Mexican Heartland: How Communities Shaped Capitalism, a Nation, and World History, 1500–2000* (Princeton: Princeton University Press, 2018), chapters 1 and 2.

[16] See John Tutino, *Making a New World: Founding Capitalism in the Bajío and Spanish North America* (Durham: Duke University Press, 2011), part 1.

[17] Tutino, *The Mexican Heartland*, chapters 4 and 5.

[18] Enrique Cárdenas, "A Macroeconomic Interpretation of Nineteenth-Century Mexico," in Stephen Haber, ed., *How Latin America Fell Behind: Essays on the Economic Histories of Brazil and Mexico, 1800–1914* (Stanford: Stanford University Press, 1997), 65–92.

[19] Tutino, *The Mexican Heartland*, chapters 6 and 7.

hurting fiscal revenues and leading to recurrent rounds of loan acquisitions, crippling debt, defaults, and political instability. Some cities, like Querétaro, lost population. Others, like Mexico City, generally maintained the level of urbanization that had existed under Spanish rule. Importantly, Mexico's textile sector began mechanizing in the 1830s – one of the earliest in the world to do so – and continued growing throughout the century and beyond.[20] In 1846, war broke out between Mexico and an expanding USA, with disastrous results for Mexico. The country lost its vast northern territories, which contained enormous agricultural, mineral, forest, and, crucially, coal and oil resources, all of which would play a central role in the rise of the USA as an industrial power by the last quarter of the nineteenth century. In essence, the war transferred huge energy resources from Mexico to the USA, with long-term implications for both countries and the world.[21]

The Mexico of the 1850s emerged from these changes. On the one hand, the country's elites kept developing a mechanized textile industry as they continued the search for alternatives to the silver economy of the past. On the other, Mexico was a more agrarian, less commercial, less dynamic nation than its 1800 predecessor. Food production was both the main occupation of the vast majority of the population and its main energy source.

## Food Energy

In the mid-nineteenth century, over ninety percent of Mexicans farmed.[22] Most of this population were subsistence farmers who depended on human and animal muscle and weather patterns to produce food. These farmers consumed the majority of their produce, selling the rest in town and city markets. Commercial farming units included ranchos and haciendas,

[20] Armando Razo and Stephen Haber, "The Rate of Growth of Productivity in Mexico, 1850–1933: Evidence from the Cotton Textile Industry," *Journal of Latin American Studies* 30, no. 3 (1998): 481–517.

[21] I thank John Tutino for this insight. A recent account of the war is Peter Guardino, *The Dead March: A History of the Mexican-American War* (Cambridge: Harvard University Press, 2017).

[22] Jesús Hermosa, *Manual de geografía y estadística de la república mejicana* (Paris: Librería de Rosa y Bouret, 1859), 83. Mexico's total population was estimated at 8,396,524 in 1861. See José María Pérez Hernández, *Estadística de la república mejicana. Territorio, población, antigüedades, monumentos, establecimientos públicos, reino vegetal y agricultura, reino animal, reino mineral, industria fabril y manufacturera, artes mecánicas y liberales, comercio, navegacion, gobierno, hacienda y crédito público, ejército, marina, clero, justicia, instruccion pública, colonias militares y civiles* (Guadalajara: Tipografía del Gobierno, 1862), 65.

which sold most of what they produced to mines, towns, and cities. In 1850, Mexico had some 14,500 ranchos and about 3,400 haciendas.[23]

Food production varied substantially by location. At the time, observers identified three broad agroecological and climatic regions within Mexico's territory.[24] First was the "hot country" (*tierra caliente*). This region encompassed the tropical lowlands along the Gulf of Mexico, the Pacific coast, and the Yucatan Peninsula. Some interior areas with a hot but dry climate, like the Tierra Caliente of Michoacán, also fit the label. In parts of these tropical lowlands, such as Yucatán, peasants practiced shifting agriculture, an itinerant form of farming that involved using the same plot of land for several years, then opening up a new patch in the forest once the former was exhausted.

The system was relatively straightforward. First, peasants cut down the forest in the middle of the dry season in January and February.[25] Forest cutting in Mexico's lowlands was energy intensive, representing about one-third of the work involved in shifting agriculture. Peasants then let the vegetation dry out until the end of the dry season (April–May) before burning it. The ashes fertilized the thin and nutrient-poor tropical soil. At the beginning of the rainy season (May–June) farmers planted maize, beans, squash, and sweet potatoes using a wooden planting stick (*coa*).[26] A first maize harvest took place in November and a second in February.

Field size was normally limited to 3 to 5 hectares, since the extreme thinness of the soils made plowing impossible, and cultivation depended entirely on human muscle. Productivity was relatively high for the first 2 or 3 years – about 1 metric ton per hectare – but typically declined by half after only 2 years, when another patch had to be cleared. The entire cycle took about 15 years to complete, at which point the farmer returned to the original plot, now covered in secondary-growth forest.

Although yields were low compared with more intensive forms of food production like irrigated agriculture or the *chinampa* system, the energy returns for shifting agriculture – the ratio of energy output (crops) to energy input (labor) – were probably high. Recent estimates for shifting cultivators in Amazonia indicate a ratio of 13.9, similar to that of wet rice

[23] Pérez Hernández, *Estadística de la República Mejicana,* 52–3.

[24] A classic description is Alexander von Humboldt, *Ensayo político sobre el reino de la Nueva España*, 4 vols. (Paris: Casa de Rosa, Gran Patio del Palacio Real, 1822), vol. 1, 70–6.

[25] The description of shifting cultivation and all figures used for my estimates are taken from José M. Regil and Alonso M. Peón, "Estadística de Yucatán," *Boletín de la Sociedad Mexicana de Geografía y Estadística* 3 (1853): 237–336. While men did most planting and crop maintenance, forest cutting involved the entire family, including children and sometimes neighbors.

[26] The *coa*'s point was often hardened with fire and, when available, tipped with iron.

cultivation in the Philippines.[27] This type of farming, however, typically supported very low population densities; areas characterized by this form of food production were among the most sparsely populated in Mexico.[28] Shifting cultivation could only feed a limited number of nonproducers, or city residents. Mérida, then the largest city in Mexico's entire tropical lowlands, had a mere 25,000 inhabitants. Yucatec farmers were frequently unable to feed the area's population, forcing the state to import grain from across Mexico or abroad.[29] Shifting cultivation also required large territories. While Yucatec farmers cultivated some 3,400 km$^2$ annually, the whole cycle required 51,000 km$^2$ or almost 40 percent of the state's territory. It is unsurprising that the encroachment of commercial agriculture on seemingly empty forest could easily threaten peasant livelihoods and prompt a violent reaction.[30] Furthermore, scarce population in agrarian societies was historically associated with forced labor. Mid-nineteenth-century Yucatán is a good example of this.[31] From an energy perspective, Yucatán's infamous coercive labor systems can be considered attempts to secure and control a crucial source of mechanical energy: human bodies.

While the transition between *tierra caliente* and *tierra templada* was fairly obvious to observers and travelers, the difference between *tierra templada* and *fría* was subtler and more arbitrary.[32] Combined, these two

[27] Tropical farmers worldwide practiced versions of shifting cultivation. There is debate about the system's energy efficiency. Anthropologists tend to portray it as an energy-efficient form of producing food with high energy returns. Some critics point out that when one considers the energy contribution of burned biomass, the system's overall efficiency declines. See David G. McGrath, "The Role of Biomass in Shifting Cultivation," *Human Ecology* 15, no. 2 (1987): 221–42.

[28] 1850s Yucatan, which included the present-day states of Yucatán, Quintana Roo, and Campeche, had 600,000 inhabitants and a population density of about 5 persons per square kilometer. See Regil and Peón, "Estadística de Yucatán." On population density for shifting cultivators, see Vaclav Smil, "World History and Energy," in *Encyclopedia of Energy* (Amsterdam; Boston: Elsevier, 2004).

[29] Mérida's status as a quasi-port city meant it could access food beyond its hinterland when shipping it by sea.

[30] See Gilbert Joseph, "From Caste War to Class War: The Historiography of Modern Yucatán (c. 1750–1940)," *Hispanic American Historical Review* 65, no. 2 (1985): 111–34.

[31] Yucatec elites thought as much. See Regil and Peón, "Estadística de Yucatán."

[32] "Temperate country" for mid-nineteenth-century Mexicans could refer to Jalapa, a town nestled in the eastern Sierra Madre at 1,300 masl (meters above sea level), with luxuriant vegetation and forests, an average annual temperature of 18 Celsius, and rainfall of 1,600 mm annually. It could also refer to Saltillo, located in the semi-arid central plateau between the eastern and western Sierra Madres at 1,600 masl, with an average annual temperature of 19 Celsius and averaging 500 mm of rainfall annually. In practice, most land within a range of 1,000 to 2,000 masl was considered "temperate," although places at lower elevations, like Monterrey (540 masl), could also fall under this category, and regions above the upper limit, like the Valley of Mexico, were included, too. The belt of land above 2,500 masl and up to the edge of the tree line was the cold region. Thus, the temperate and cold areas encompassed the massive parallel Sierra Madres running through Mexico from north to south, the volcanic range crisscrossing them in an east–northwest direction to form the central highlands, and the semi-arid plateau extending north of the latter to the US border.

geographies made up two-thirds of the country, included the most productive agricultural lands, and supported the largest populations.[33] Particularly fertile were the valleys of the central highlands and the area to the north, known as the Bajío. While the Bajío only came under cultivation during Spanish rule using animals and European irrigation technologies, the intermontane central valleys had produced most of the food in what is now Mexico since pre-Columbian times. These places concentrated most of mid-nineteenth-century Mexico's energy in the form of food and human and animal biological converters.[34] Agriculture in the state of Querétaro and the Valley of Mexico illustrates how systems of food production worked in the Bajío and the central highlands.

In 1850, Querétaro was one of Mexico's wealthiest states.[35] It enjoyed a relatively robust system of food production reliant on human muscle, many draft animals, and even water-powered machinery. With 180,000 people living in one of the smallest territories in the country, Querétaro's population density was three times that of Yucatan. About 70 percent of the state was under exploitation. Land ownership primarily consisted of haciendas and ranchos, which controlled 39 percent of the territory, while pueblos owned a mere 2 percent.[36] The overwhelming majority of farmers practiced rain-fed agriculture.[37] Less than half of 1 percent of land was irrigated, mostly belonging to haciendas. Tens of thousands of oxen, horses, mules, and donkeys pastured on roughly 30 percent of the state's land.[38] These animals moved winches (*malacates*) in mines, pulled plows in

[33] Five states – Guanajuato, Jalisco, México, Puebla, Querétaro, plus the Valley of Mexico – concentrated 45 percent of the country's population. See Pérez Hernández, *Estadística de la República Mejicana*, 63.

[34] Environmental boundaries were determined by technology, population level, social organization, forms of resource use, and other factors. The flexibility of these boundaries is attested by the much larger and denser populations of pre-Columbian societies in the central highlands of Mexico on the eve of the Spanish invasion.

[35] "Notas estadísticas del Departamento de Querétaro," *Boletín de la Sociedad Mexicana de Geografía y Estadística* 3 (1852): 169–236. This source calculated the state's area at 856 square leagues or 15,180 km$^2$ (the present-day estimate is 11,699 km$^2$). My estimations of agricultural productivity and energy flows rely on these figures and are therefore mere approximations.

[36] The state had 124 haciendas and 398 ranchos at the time, but over the next two decades experienced a process of land concentration by haciendas and a decline in the number of ranchos. See Marta García, *Querétaro: historia breve* (México, D. F.: FCE, 2010), 203–6.

[37] Catalina Rodríguez and Beatriz Scharrer, "La agricultura en el siglo XIX," in *La agricultura en tierras mexicanas desde sus orígenes hasta nuestros días* (México, D. F.: Conaculta, 1991), 217–54. Simon Miller, "The Mexican Hacienda between the Insurgency and the Revolution: Maize Production and Commercial Triumph on the Temporal," *Journal of Latin American Studies* 16, no. 2 (1984): 309–36.

[38] It is unclear how grazing land was distributed, but it's safe to assume haciendas and ranchos controlled much of it.

fields, and carried loads on roads. Draft animals in mid-nineteenth-century Querétaro produced the energy output of 270,000 men.[39] They were so important that a “hacienda or rancho without pastureland [was] considered of little value.”[40] The period’s ratio of farmed land to pasture in Querétaro reveals one major energy constraint all agrarian societies faced: more land allotted to raising draft and burden animals meant less land for feeding human beings. In turn, feeding animals and human beings directly threatened woodlands, the main source of heat energy. In other words, if one wanted more wood to, say, increase iron production, it was at the expense of growing food to feed humans and animals. One simply could not augment all forms of energy simultaneously. For an agrarian society such as mid-nineteenth-century Querétaro, “the problem of energy utilization was one of alternative land uses.”[41]

Querétaro farmers developed ingenious strategies for expanding the number of farm animals without expanding the amount of land under cultivation. Much like their European counterparts, Querétaro farmers grazed animals in the forest for half of the year, effectively making forest ecosystems “subsidize” human husbandry. During the rainy-summer season, livestock was brought to forested areas to feed on plants like *quelite* and *romerillo*.[42] During the dry-winter season, livestock depended on a mix of cultivated and wild crops like clover (*trébol*), wild oats, nopal cactus, mesquite, and maize and bean stalks. Alfalfa, wheat, and barley straw were reserved for time spent in pens. While it is hard to estimate its impact, this practice undoubtedly deprived forests of litter and essential nutrients and likely reduced the forest’s biomass capacity.

[39] In 1850, there were 26,035 oxen, 9,017 horses, 3,544 mules, and 3,510 donkeys. I assume that 1 horse’s energy output equals 10 men; 1 ox’s, 6 men; 1 mule’s, 5 men; and 1 donkey’s, 2 men. I follow Astrid Kander and Paul Warde, *Number, Size, and Energy Consumption of Draught Animals in European Agriculture*, Working Paper, March 2009.

[40] “Notas estadísticas del Departamento de Querétaro.”

[41] Sieferle, *The Subterranean Forest*, 25. This constraint played out even at the level of crops themselves. The maize plant grown at the time, unlike more modern, “high-yielding” varieties, devoted much of its energy to developing large stalks and husks. Farmers in Mexico grew this type of maize because these parts, which could not be directly consumed by humans, were essential fodder for animals. The high-yielding, short-stalk varieties that exist today are only viable in a society where animals do not play the role of power source. See David Clawson and Don Hoy, “Mexico: A Peasant Community that Rejected the ‘Green Revolution’,” *The American Journal of Economics and Sociology* 38, no. 4 (1979): 371–87. In 2016, only 6.7 percent of Querétaro’s territory was pasture. See INEGI, *Anuario estadístico y geográfico de Querétaro 2017* (Aguascalientes: INEGI, 2017).

[42] *Quelite* is a generic term for various plants of the genera *Amaranthus* and *Chenopodium*. *Romerillo* is a common name for *Asclepias linaria*, *Baccharis sarothroides*, and *Bidens alba*. On the Bajío’s original vegetation, see Butzer and Butzer, “The Natural Vegetation of the Mexican Bajio.”


Figure 1.1 Zapotec peasant in Oaxaca with wooden plough and oxen, the most common draft animal in nineteenth-century Mexico, ca. 1870.
Source: Fototeca INAH.

The final piece in Querétaro's agrarian system was farm technology.[43] Farmers used a variety of technologies to increase production. The wooden plough was a fundamental instrument, tipped in iron or with an iron-tipped moldboard. In Mexico, a yoke of two oxen was common (see Figure 1.1). The yoke was driven by one man (*gañán*) followed by another who cast the seeds into the ground (*sembrador*). In general, Querétaro's cultivated areas had light soils,[44] so it is possible a yoke could plow more land daily than the typical 0.4 hectares of land that a team of two oxen could plow in the heavy soils of northern Europe, but we simply lack the information to say this with certainty. Normally, haciendas owned both ploughs and oxen and provided them to sharecroppers,[45] but with only 124 recorded haciendas in the state at the time compared with 8,000 ploughs, it appears that this technology was widely available.[46] Shovels, hoes, wagons, digging sticks, pitchforks, and

43 "Notas estadísticas del Departamento de Querétaro."
44 Pheozems and vertisols, with some heavier luvisols in the south. See INEGI, *Anuario Estadístico y Geográfico de Querétaro 2017*, map 12.
45 Miller, "The Mexican Hacienda between the Insurgency and the Revolution."
46 The figure is from an 1840s state census. See "Notas estadísticas del Departamento de Querétaro."

sickles were also common. Some haciendas (Tequisquiapan, for example) introduced locally made, likely water-powered machines to winnow and shell maize and wheat. They also employed threshing machines to separate straw from wheat grain. Estimates suggest that these machines reduced production costs by 35 percent. But mechanical winnowers and threshers were only accessible to heavily capitalized haciendas, so their impact on overall farm productivity in the state likely remained small.

Rain-fed agriculture in the Valley of Mexico (and across much of the *tierra templada* and *fría*) looked fairly similar to that practiced in Querétaro. What was unique to the Valley of Mexico was the wet, raised-bed agriculture system known as *chinampas*. Though diminished from its heyday in the early sixteenth century, when it covered over 100 square kilometers, *chinampa* agriculture remained important in mid-nineteenth-century Mexico. Once widespread across the lake system, by the nineteenth century, *chinampas* were largely confined to the shores of lakes Chalco and Xochimilco and the towns of Santa Anita, Ixtacalco, and Mexicalzingo. Like their colonial predecessors, nineteenth-century chinamperos first located an underwater mound (*cimiento*) by sounding out the bottom of the canal with an oar. Once found, peasants fenced the mound with reeds.[47] They then piled up alternating layers of lake mud and aquatic vegetation, known in Nahuatl as *atapalácatl*, until the mound was some 20–25 centimeters above water level. Willow trees or *huejote* were planted along the edges of the *chinampa* in order to stabilize the soil. The size of *chinampa* plots varied widely, from a few meters to the size of several modern soccer fields.[48]

*Chinampas* produced several crops annually and were never left fallow. With the exception of a few vegetables – radish, turnip, and carrot – most plants were first grown in nursery beds (*almácigos*) and then transplanted to the main *chinampa*. Maize continued to be the most important crop cultivated in *chinampas*, both for local consumption and for market in Mexico City and other large population centers in the valley. Tomatoes, chili pepper, cabbage, cauliflower, lettuce, green tomatoes, Brussels sprouts, onion, spinach, and celery were also grown. Yields were sustained over time by adding aquatic vegetation and lake mud before every planting.[49] In the early sixteenth

[47] *Chinampa* comes from the Nahuatl *chinamitl*, meaning "cane enclosure."

[48] The largest were up to 900 meters long and 6 meters wide, or 5,400 square meters, with most measuring about 90 square meters. See Miguel Santamaría, *Las chinampas del Distrito Federal: informe rendido al señor Director General de Agricultura* (Mexico: Impr. y Fototípia de la Secretaría de Fomento, 1912), 18. A singles tennis court is 195 square meters, or 24 meters long by 8 meters wide.

[49] Santamaría, *Las chinampas del Distrito Federal*, 15–16. Although published in the early twentieth century, Santamaría based his work on interviews with old peasants ("cultivadores ancianos"). It is reasonable to assume that this information can also be applied to the nineteenth century. See also

century, *chinampa* agriculture yielded on average 3 tons of maize per hectare and supported over 170,000 people with per capita annual consumption around 160 kilograms. Assuming a population of 200,000 for Tenochtitlan in 1519, *chinampas* provided 85 percent of the food requirements of the Mexica capital.[50] This was an extraordinary level of productivity, matched only by twentieth-century farming methods using mechanization and synthetic fertilizers. There is evidence that such levels of *chinampa* productivity remained stable as late as the nineteenth and early twentieth centuries.[51]

Given that most energy in agrarian societies came from food, how much surplus a farming system could produce mattered greatly. How much of this surplus the state or urban elites could force subsistence farmers to give up – an inherently political question – also mattered. Surplus food determined the size (and location) of nonfarming populations, meaning cities and towns.[52] Around 1860, Mexican farmers produced enough food for a mere 10 percent of the total population to live in cities (Table 1.1). This urban population was not homogeneously distributed across Mexico but concentrated in areas with the richest farmland in the country.

With a population of about 200,000 residents, it is no coincidence that Mexico City was by far Mexico's most populated urban center in the 1850s (Puebla came in a distant second with 70,000 inhabitants). No other region in the country surpassed the Valley of Mexico's productive system of *chinampas* and rich alluvial plains.[53] As the largest market in the nation, Mexico City also attracted producers from outside the valley. Mexico's very high land

Antonio García Cubas, *Geografia e historia del Distrito Federal* (México: Antigua Imprenta de Murguía, 1894), 19.

50 The estimate for pre-Hispanic *chinampa* productivity is in William Sanders, "The Agricultural History of the Basin of Mexico," in *The Valley of Mexico: Studies in Pre-Hispanic Ecology and Society* (Albuquerque: University of New Mexico Press, 1976), 101–60. A detailed description of late colonial *chinampa* agriculture can be found in José Antonio de Alzate y Ramirez, *Gacetas de literatura de México*, vol. 2 (Puebla: Reimpresas en la Oficina del Hospital de San Pedro, 1831), 382–95. A description of colonial *chinampa* agriculture in the Valley of Mexico is Gibson, *The Aztecs under Spanish Rule,* 320–1. Gibson observes that *chinampa* agriculture was still practiced in reduced areas in the salt lakes (including Texcoco) during colonial times. See also Teresa Rojas Rabiela, *La agricultura chinampera: compilación histórica* (Chapingo: Universidad Autónoma Chapingo, 1983).

51 Rojas Rabiela claims that early twentieth-century *chinampas* yielded an unlikely average of 5–6 tons per hectare, almost twice as much as the 3 tons per hectare proposed for pre-Hispanic *chinampa* agriculture. Even if Rojas Rabiela's figure is inaccurate, it suggests that *chinampa* productivity did not decline over time. See Rojas Rabiela, "Ecological and Agricultural Changes in the Chinampas of Xochimilco-Chalco," in *Land and Politics in the Valley of Mexico: A Two Thousand-Year Perspective* (Albuquerque: University of New Mexico Press, 1991).

52 Not all nonfarming populations lived in cities; these included several thousand miners, mule train drivers, and so on.

53 William Sanders estimated an average yield of 1,400 kg per hectare of alluvial land in the Valley of Mexico during pre-Hispanic times. See Sanders, "The Agricultural History of the Basin of Mexico," 144.

Table 1.1 *Estimate of rural and urban population in Mexico, 1856*

| Type of Population | Number | Percentage |
|---|---|---|
| Rural | 7,443,309 | 90.3 |
| Urban | 804,351 | 9.7 |
| Total | 8,247,660 | 100 |

*Source:* Jesús Hermosa, *Manual de geografía y estadística de la República Mexicana*, 1857, 83.

transportation costs at the time limited the amount of food that could reach Mexico City, or any city, from other regions. But Mexico City's lake system – which connected the downtown area and rich hinterland in the south and southeast of the valley – made it the country's only noncoastal major city with access to cheap water transportation.[54] By contrast, the average population size for other capital cities in 1850 Mexico was 24,000 inhabitants. A city's population in mid-nineteenth-century Mexico, then, indicated the productivity of its agrarian hinterland and the city's capacity to access its surplus. As following chapters illustrate, cities played a central role in Mexico's energy transition to fossil fuels, so this national urban geography based on local agrarian productivity had long-term implications.

The solar energy regime also shaped how urban spaces were utilized and limited the size they could achieve.[55] In the 1850s, Mexico City had an area of about 10–11 km$^2$, large by contemporary standards.[56] Although

[54] This hinterland provided mid-nineteenth-century Mexico City residents with an annual bounty of 17,000 head of cattle, 280,000 sheep (*carneros*), 60,000 pigs, 1,260,000 chickens, 125,000 ducks, 250,000 wild turkeys, 65,000 pigeons (*pichones*), 140,000 quails and partridges (*codornices y perdices*), 118,000 three-fanega maize *cargas* (16,284,000 kilograms, assuming 138 kilograms per *carga*), 130,000 wheat flour *cargas* (20,930,000 kilograms), 300,000 pulque *cargas*, 12,000 aguardiente barrels, and over 68,000 kilograms of oil. See Marcos Arróniz, *Manual del viajero en Méjico, ó, compendio de la historia de la Ciudad de Méjico, con la descripcion e historia de sus templos, conventos, edificios públicos; las costumbres de sus habitantes, etc., y con el plan de dicha ciudad* (Paris: Librería de Rosa y Bouret, 1858), 39. Notice the importance of meat for urbanites' diet. Given that people and animals competed for food in agrarian societies, overpopulation usually meant giving up meat. A plant-based diet can feed about eight times the population of a meat-based one. The abundance of meat in mid-nineteenth-century Mexico City suggests relatively low population pressure. See Sieferle, *The Subterranean Forest*, 18.

[55] Sieferle calls this principle the "minimization of transport." See Sieferle, *The Subterranean Forest*, 45.

[56] Mexico City and its metropolitan area covered some 1,500 km$^2$ in the early twenty-first century, 150 times more than its nineteenth-century predecessor. López Rosado estimated (without citing sources) that in 1858, Mexico City had an area of 8.5 square kilometers, increasing to 40.5 square kilometers by 1910, a growth of 4.7 times in half a century. He gives a population figure of 200,000

minuscule compared with its present-day size (about 1,500 km$^2$), it was extremely difficult for a city relying on transport by humans and draft animals to expand beyond the boundaries that both could traverse efficiently in a short period. Such constraints had many repercussions for urban life. For one, it forced people of different classes to live in close proximity. A recurring theme in the period's travel literature is the disgust elites felt sharing urban spaces with *léperos* (urban underclass) and other members of the lower classes. Small cities also shaped routines of everyday life. Work and private life often existed under the same roof. Workshops and stores typically devoted the first floor to business and the second to living quarters. Under the solar energy regime, cities concentrated energy in every form, from animal and human bodies to food resources and material goods.[57] To keep the circulation of energy efficient, urban spaces had to remain small.

In sum, food production was the basis of mid-nineteenth-century Mexican society. While some indigenous groups in the north still subsisted as hunter-gatherers,[58] the vast majority of Mexicans depended on agriculture. From an energy perspective, hunter-gatherers largely tapped the flow of solar energy without regulating it. Agriculturalists, on the other hand, controlled this flow. They replaced an enormous variety of natural vegetation with a few selected plants, concentrating dispersed energy into their crops. Like farmers in other agrarian societies, Mexican food producers managed a number of constraints and risks. Some of these constraints were more or less fixed, such as the amount of land that could be cultivated using animal power. Others were cyclical in nature, like devastating El Niño–induced droughts.[59] Population growth was relatively slow and fluctuated depending on harvests, epidemics, natural disasters, and war.[60]

## Forests

Photosynthesis is the basis of life on earth. Plants, trees, and phytoplankton (aquatic plants) are the only organisms capable of photosynthesizing or

in 1858 and 471,000 in 1910. See Diego G. López Rosado, *Historia del abasto de productos alimenticios en la Ciudad de México* (México, D. F.: Fondo de Cultura Económica, 1988), 152.

57 A demographic analysis of cities in nineteenth-century Mexico is Richard E. Boyer, "Las ciudades mexicanas: perspectivas de estudio en el siglo XIX," *Historia Mexicana* 22, no. 2 (1972): 142–59.

58 E. Lamberg, "Inspección de las colonias militares de Chihuahua," in *Boletín de la Sociedad Mexicana de Geografía y Estadística*, vol. III (México, 1852), 19–25.

59 Blanca Mendoza et al., "Historical Droughts in Central Mexico and Their Relation with El Niño," *Journal of Applied Meteorology* 44, no. 5 (2005): 709–16.

60 María Eugenia Romero and Luis Jáuregui, "México 1821–1867. Población y crecimiento económico," *Iberoamericana* III, no. 12 (2003): 25–52.

fixing incoming solar radiation for their own growth. They sustain the majority of multicellular life-forms, which eat either plants or plant-eaters. Plants and trees capture less than 1 percent of all the solar radiation that reaches earth, and only a fraction of that amount is transformed into plant tissue. This all means that the total amount of plant matter in any given place sets a *limit* to the energy that can be harvested. Such a limit imposes ecological constraints on societies that use wood for heat energy. A close look at wood use in households, factories, mines, and other mid-nineteenth-century industries will illustrate this connection.

Although pre-Columbian indigenous civilizations proved perfectly capable of overexploiting forests, the real assault on Mexico's forests began with colonial mining.[61] Over three centuries, successive cycles of expansion, stagnation, decline, and renewed growth on a larger scale – coupled with colonial mining of silver, gold, and other metals – took a considerable toll on Mexico's forests. The central highlands, the two Sierra Madres, and the northern plateau's "mining belt" were particularly hard-hit. One study suggests that under Spanish rule, some 315,000 $km^2$ of pine-oak and mesquite forest – an area slightly larger than Italy – may have been cut in the mining belt to meet the voracious fuel demands of smelting and refining.[62] Another estimate proposes a much smaller overall impact of colonial mining, about one fourth of the deforested area.[63] Despite disagreement, it is clear that the silver currency that powered the global economy of the early modern period, filled the coffers of European merchants, and circulated in distant Chinese markets[64] literally consumed Mexico's forests. If one considers the deforestation caused by other fuel-hungry industries like iron and glass, along with the comparatively less demanding expansion of agriculture and animal

[61] Sherburne Friend Cook, *The Historical Demography and Ecology of the Teotlalpan* (Berkeley: University of California Press, 1949), 31–3.

[62] Daviken Studnicki-Gizbert and David Schechter, "The Environmental Dynamics of a Colonial Fuel-Rush: Silver Mining and Deforestation in New Spain, 1522 to 1810," *Environmental History* 15 (2010): 94–119. One potential problem: Studnicki-Gizbert does not consider the average biomass productivity of different types of Mexican forests, which directly influences the forest area that needed to be cut for fuelwood production. He also assumes that charcoal making in Mexico always caused deforestation, ruling out possible forms of sustainable wood harvesting.

[63] See Saúl Guerrero, "The Environmental History of Silver Refining in New Spain and Mexico, 16c to 19c: A Shift of Paradigm" (PhD Dissertation, McGill University, 2015), 554. Guerrero claims that some 70,000 $km^2$ were deforested during colonial times. Another important study favoring smaller areas of deforestation is Robert C. West, *The Mining Community in Northern New Spain: The Parral Mining District* (Berkeley: University of California Press, 1949), 45–6.

[64] Richard von Glahn, "Foreign Silver Coins in the Market Culture of Nineteenth-Century China," *International Journal of Asian Studies* 4, no. 1 (2007): 51–78.

husbandry, the true scale of New Spain's deforestation comes further into focus.[65]

It is very likely, then, that Mexico's independent history began with large parts of its territory deforested. "Forest" and "wood," however, are generic terms that obscure a huge diversity of types, conditions, histories, ecologies, and energy densities.[66] Where were Mexico's forests located in 1850? What type of forests were they? What was their extension and condition? A combination of altitude, latitude, precipitation, temperature, and soil composition determine forest type.[67] In broad terms, this means that vegetation is typically more abundant in areas of Mexico closer to the equator and decreases as one moves north. Mexico's tropical lowlands came in two basic forms: 1) an evergreen rainforest with a tall canopy (up to 40 meters), average rainfall of over 2,000 mm annually, and high temperatures year-round and 2) a dry, deciduous tropical forest with a lower canopy (up to 20 meters) and a stark divide between rainy and dry seasons. These dry forests extended along Mexico's Pacific coast and into the Yucatan Peninsula, shading into thorny woodland and eventually a scrub forest in northern latitudes. Mexico's highlands supported montane forests, mostly fir, pine-oak, and oak forests. About a third of Mexico's territory, mostly northern, was occupied by xerophytic brush vegetation, which turned into grasslands in areas with higher precipitation and adequate conditions.[68] Of course, these "theoretical" forest zones were heavily modified by human action by 1850, some

[65] On Mexico's colonial forest history, see Antony Challenger, *Utilización y conservación de los ecosistemas terrestres de México: pasado, presente y futuro* (México, D.F.: Comisión Nacional para el Concimiento y Uso de la Biodiversidad, 1998); Andrés Lira, "Los bosques en el virreinato (apuntes sobre la visión política de un problema)," *Relaciones* 11, no. 41 (1990): 117–27; Manuel Lucena Giraldo and Luis Urteaga, *El bosque ilustrado: estudios sobre la política forestal española en America* (Madrid: Instituto Nacional para la Conservación de la Naturaleza: Instituto de la Ingeniera de España, 1991).

[66] *Monte* and *bosque* were originally Spanish colonial legal terms, not necessarily descriptive categories of vegetative cover (much like "woodland" and "forest" in most of Western Europe). Spanish forest codes typically used *monte* to refer to any wooded area. See *Real ordenanza para el gobierno de los montes y arbolados de la jurisdicción de marina* (Madrid: Imprenta Real, 1803). See also Paul Warde, "Fear of Wood Shortage and the Reality of the Woodland in Europe, c. 1450–1850," *History Workshop Journal*, no. 62 (Autumn 2006): 28–57.

[67] Latitude influences how much sunlight a given place receives for photosynthesis. Temperature decreases by roughly 1 °C per 100 meters and affects plant growth. Soil composition is closely related to climate.

[68] Overviews of Mexico's vegetation types are Jerzy Rzedowski, *Vegetación de México* (México, D. F.: Conabio, 2006); SEMARNAT, *Atlas Geográfico del Medio Ambiente y Recursos Naturales* (México, D. F.: SEMARNAT, 2006). Philip L. Wagner, "Natural Vegetation of Middle America," in *Handbook of Middle American Indians. Volume One: Natural Environment and Early Cultures* (Austin: University of Texas Press, 1964).

even largely products of it. Consider the scrublands that cover vast areas in the mining belt of northern Mexico, once populated by a variety of dry oak, poplar, and willow forests; most were felled to fuel silver mining.[69] Other forest types regrew following heavy human disturbance, including tropical forests in the Maya area, but with concentrations of plant species useful to human beings that would not occur in the absence of anthropogenic influence.

Although there is little information for accurately estimating forest cover in Mexico by the mid-nineteenth century, it is possible to make some rough calculations. One source from the early 1860s suggested that about 14–15 percent of the country's total area was devoted to agriculture, 9–10 percent was fallow farmland, 8–9 percent was pasture and meadows, 6–7 percent was partially wooded (*montes*), a mere 4 percent was forest (*bosques*), and the remaining 55–60 percent consisted of human settlements, uncultivated or unmanaged land, rivers, and lakes.[70] Woodland and forest may have covered 10–15 percent or roughly 200,000–300,000 $km^2$ of Mexico in the middle of the nineteenth century (Table 1.2).[71]

Limited forest cover in densely populated areas created severe problems for mid-nineteenth-century Mexico's wood-based civilization. Various nonfuel uses exerted constant pressure on local timber stands. While typically walled with lime-mortared stones, wealthy homes required large amounts of timber for flooring and roofing. The poor also used wood for the frames of their homes when it was available. As mentioned before, most farming implements were made of wood, as was complex machinery like waterwheels. Some waterwheels had enormous dimensions, a testament not only to wood's versatility but to sophisticated wood craftmanship. Wooden coaches were also common, although by the mid-nineteenth

[69] Daviken Studnicki-Gizbert, "Exhausting the Sierra Madre: Mining Ecologies in Mexico over the Long Durée," in John R. McNeill and George Vrtis, eds., *Mining North America: An Environmental History since 1522* (Berkeley: University of California Press, 2017), 19–46.

[70] Pérez Hernández, *Estadística de la República Mejicana*, 58–9. Emiliano Busto, *Estadística de la República Mexicana. Resúmen y análisis de los informes rendidos á la Secretaría de Hacienda por los agricultores, mineros, industriales y comerciantes de la República y los agentes de México en el exterior, en respuesta á las circulares de 1° de Agosto de 1877* (México: Imprenta de Ignacio Cumplido, 1880), vol. II, 422. Busto agrees with Pérez Hernández regarding forest cover but almost triples the area for woodland *(montes)* at 16 percent of Mexico's total area. (A typo in Busto's original suggests he took the forest figure from Pérez Hernández.)

[71] For comparison, in 2002 Mexico's forests represented 34 percent of its total area. See SEMARNAT, *Atlas geográfico del medio ambiente y recursos naturales*, 10. At 10–15 percent forest cover, Mexico fared better than most of Europe, where forest covered around 6 percent of western and central Europe in 1850. See Jed O. Kaplan, Kristen M. Krumhardt, and Niklaus Zimmermann, "The Prehistoric and Preindustrial Deforestation of Europe," *Quaternary Science Reviews* 28, no. 27 (2009): 3016–34. See also Warde, "Fear of Wood Shortage."

Table 1.2 *Estimate of distribution of land cover in Mexico, ca. 1860*

| Type of Land Cover | Area (km²) | Percentage |
|---|---|---|
| Forest | 83,825 | 4.0 |
| Woodland | 142,345 | 6.8 |
| Cultivated | 326,025 | 15.7 |
| Fallow | 215,600 | 10.4 |
| Grassland and Meadows | 196,630 | 9.5 |
| No Cultivation | 1,099,385 | 53.2 |
| Total | 2,063,810[72] | 100 |

*Source:* Hernández, *Estadística de la República Mexicana*, 58–9.[73]

century US-made coaches became popular. In short, wood was easily the most important construction material for mid-nineteenth-century Mexicans.

But wood's most important role was as a source of heat energy.[74] Virtually every Mexican household cooked using wood or charcoal in iron stoves or with iron or copper-made pots. Peasants everywhere made tortillas by placing flat iron griddles (*comal*) over a wood or charcoal open fire. Meat was also roasted over open flame. Only in wood-poor areas did the rural population resort to using animal dung, corn husks, dry maguey leaves, or any combustible material available.[75] We lack precise figures for domestic fuel consumption in mid-nineteenth-century Mexico, especially rural consumption. Still, it is likely that people in the countryside survived with 1–2 kg of

72 Mexico's actual total area is 1,973,000 km²; Pérez Hernández overestimated its area by 90,810 km².

73 Given that figures for the vast tropical lowland forests were nonexistent at the time, the area Pérez Hernández included under "forest" or "woodland" likely referred to the temperate forests of the central highlands and the Sierra Madres and the arid woodland that covered most of the Bajío and northern and western Mexico – all woods historically exploited since colonial times. It is also possible that Pérez Hernández considered the southern and lowland dry and humid tropical forests, wetlands, and mangrove forests, which lay beyond 1850 Mexico's core agrarian nucleus, as "uncultivated." While covering tropical forests of a later period, see Herman W. Konrad, "Tropical Forest Policy and Practice During the Mexican Porfiriato, 1876–1910," in Harold K. Steen and Richard P. Tucker, eds., *Changing Tropical Forests: Historical Perspectives on Today's Challenges in Central and South America* (Durham: Duke University Press, 1992).

74 And light. Urban lighting depended on turpentine (*trementina*), an oil derived from pine resin. See "Alumbrado de trementina," *El Monitor Republicano*, January 13, 1850.

75 Sociedad Mexicana de Geografía y Estadística, *Boletín de la Sociedad Mexicana de Geografía y Estadística*, vol. II (México: Sociedad Mexicana de Geografía y Estadística, 1850), 375.

wood daily, if figures for urban and statewide consumption are any indication.[76] Residents in the city of Querétaro, by contrast, had access to about 2–2.5 kg of wood per day.[77]

It is possible to roughly calculate mid-nineteenth-century Mexico's domestic fuel consumption and its environmental impact. Most sources agree that the country's population in the 1850s hovered around eight million. If we take an average daily consumption of 2 kg of wood per capita, Mexico's population used some 16,000 metric tons of wood every day or 5,840,000 metric tons annually. Assuming an average annual growth of 600 metric tons of wood per square kilometer, Mexicans in the 1850s required the yearly product of 9,733 $km^2$ of forest or an area somewhat smaller than the state of Querétaro to cook their meals, warm themselves, and otherwise cover their domestic needs. This represented between 3.2 and 4.8 percent of Mexico's total forest area at the time. Such a vast extension of forest, of course, was only needed if people were harvesting their forests sustainably, that is, restricting themselves to extracting their forests' annual growth. A significantly smaller territory would have been needed if people had simply clear-cut. Many mines had

[76] Sherburn Cook estimated that a five-member family in early sixteenth-century Mexico consumed 10 kg of firewood daily. See Cook, *The Historical Demography and Ecology of the Teotlalpan*, 32. This conforms with average fuel consumption in northern Europe, which ranged from 1 kg daily in Mediterranean regions to 3 kg in northern latitudes. See Warde, "Fear of Wood Shortage." Rural Mexicans in 2010, many of whom continued using fuelwood, consumed a daily average of 2.4 kg of wood per capita, ranging from 1.4 kg in semiarid regions to 2.9 kg in tropical humid areas. See Miguel Caballero Deloya, "La verdadera cosecha maderable en México," *Revista Mexicana de Ciencias Forestales* 1, no. 1 (2010): 5–16. This all suggests that a similar level of fuelwood consumption has persisted among rural Mexicans for over 400 years.

[77] Querétaro's population was about 27,000 (down from over 50,000 in 1800); the inhabitants consumed 7,590 metric tons of charcoal in 1844. That represented 0.3 kg of charcoal per person. Assuming a ratio of 20 percent of wood to charcoal, every urban resident could access about 1.4 kg of wood as charcoal. Records also put statewide consumption of fuelwood in 1844 at 149,873 metric tons, or about 0.8 kg per capita. Thus, urban residents in Querétaro consumed on average 2–2.5 kg of wood daily, either as fuelwood or as charcoal. If we suppose a similar consumption level across the entire state, its 180,000 inhabitants required 360,000 kg of wood (as fuelwood or charcoal) or 360 metric tons *daily* – 131,400 metric tons per year. When one converts this figure into forest area, Querétaro's population required the annual growth of 219 $km^2$ of forest every year simply to meet domestic needs. All figures come from "Notas estadísticas del Departamento de Querétaro." The conversion formula is 1 *carga* = 138 kg; 55,000 charcoal *cargas* = 7,590 metric tons; and 1,086,034 *cargas de leña* = 149,873 metric tons. For converting metric tons of wood into forest area, I assume an average annual wood growth or net primary productivity of 6 metric tons per hectare or 600 metric tons per square kilometer. Of course, annual wood growth varies substantially depending on forest type; here I use the average for temperate oak and pine-oak forests, characteristic of Mexico's central highlands and the *monte* of northern Mexico. Leopoldo Galicia et al., "Perspectivas del enfoque socioecológico en la conservación, el aprovechamiento y pago de servicios ambientales de los bosques templados de México," *Madera y Bosques* 24, no. 2 (2018) offers a range between 5.8 and 10.7 metric tons of wood per hectare annually for Mexico's temperate forests.

the financial means to bring fuel over long distances, and itinerant industries like ironworks could move to a new area once local forest was depleted. But most communities in Mexico were attached to their land and depended on local forests. They probably sought to ensure the long-term availability of woods and avoided clear-cutting unless necessary.

Woods, especially fuelwood, were also necessary for a variety of manufacturing and extractive industries in mid-nineteenth-century Mexico. Ironworks, glassworks, and saltworks all required large amounts of wood energy. Throughout the colonial period and until the mid-nineteenth century, Catalan forges produced virtually all of Mexico's iron.[78] In these forges, an open charcoal fire melted the iron ore. A trompe, a device in which water fell through perforated pipes to produce an air blast, intensified the heat of the open fire. Workers then used a waterwheel-powered hammer to work the mass of wrought iron into bars, which merchants sold at local markets for approximately 6 to 8 cents per kilogram.[79] Due to the exorbitant cost of transporting wood and charcoal over long distances, ironworks were typically located in mountainous, forested regions close to their fuel sources. Indian and peasant charcoal makers would enter the forest, where they felled, cut, and split the trees.[80] After cutting the wood into small pieces, the charcoal makers stacked them in mounds. Leaving the center of the mound hollow to serve as a chimney, they covered it with leaves or grass and dirt to seal it. The charcoal makers then burned the mound and, in a process that could take up to 2 weeks, controlled the fire, making certain no holes emerged in the structure. Human porters or donkeys then transported the charcoal in bags to furnaces.[81]

[78] Estanislau Tomás, "The Catalan Process for the Direct Production of Malleable Iron and Its Spread to Europe and the Americas," *Contributions to Science* 1, no. 2 (1999): 225–32; Gerardo Sánchez Díaz, "Los orígenes de la industria siderúrgica mexicana. Continuidades y cambios tecnológicos en el siglo XIX," *Tzintzun: Revista de Estudios Históricos*, 50 (2009): 11–60.

[79] In the Valley of Mexico, many ironworks remained small well into the twentieth century. One ironworks founded in 1904 in Mexico City was worth only 20,000 pesos, had 50 workers, and exploited only 15 horsepower. See "La Secretaría de Fomento remite boletas para recoger datos relativos a la estadística industrial del Distrito" 1907, Secretaría de Gobierno del D.F., Estadísticas, caja 1, exp. 31, AHDF. The description of Catalan forges is based on John Birkinbine, *Industrial Progress of Mexico* (Philadelphia: no publisher identified, 1909), 13–15.

[80] Some indigenous communities in central Mexico were largely charcoal-makers. In San Bernabé, a typical mountain peasant community in the Valley of Mexico, 62 percent of males made charcoal in the late 1860s. See "Padrón de los habitantes del pueblo de San Bernabé de la Municipalidad de San Ángel" (1868), Tlalpan, Estadísticas, caja 89, exp. 3, AHDF.

[81] "Charcoal in Mexico," *Journal of the United States Association of Charcoal Iron Workers*. 3, no. 1 (1882): 8–11. See also Patricia Fournier, "Indigenous Charcoal Production and Spanish Metal Mining Enterprises: Historical Archaeology of Extractive Activities and Ecological Degradation in Central and Northern Mexico," in Marcos de Souza and Diogo Costa, eds., *Historical Archaeology and Environment* (Cham: Springer, 2018), 87–108.

In the mid-nineteenth century, a traditional ironworks consumed 6.3 metric tons of charcoal (32 tons of fuelwood) to produce 1 ton of pig iron. A Catalan forge in Durango in the 1830s consumed in 1 week the same amount of wood that 19 hectares of forest yielded in a year.[82] Put another way, a typical ironworks in mid-nineteenth-century Mexico could, in a single year, exhaust the entire annual wood growth of a forest area equivalent to Mexico City's total surface area in the 1850s (about 10 km$^2$). In some cases, the real consumption would have been much lower, since some ironworks operated for about half of the year. Nevertheless, Lucas Alamán, the great Mexican historian and statesman, noted in the 1840s that "the consumption of fuel by ironworks requires that woodlands *be carefully managed* or soon these establishments will run out of charcoal."[83]

The production of wood-fired iron faced clear environmental limits. Suppose a total of 200,000 km$^2$ of forest in mid-nineteenth-century Mexico. Assuming a very rough annual average productivity of 600 metric tons of wood per square kilometer, such a forest area yielded some 180,000,000 metric tons of dry wood annually. Even if the *entire* annual forest yield of Mexico had been harvested to fuel ironworks (which obviously never happened), total production would have been 5,625,000 metric tons of pig iron, well below present-day outputs. As an essential component of industrialization, these estimates illustrate the clear limits to large-scale iron production under Mexico's solar energy regime.[84]

But Mexico's largest consumer of fuelwood, both historically and in the 1850s, was mining. There were hundreds of mines all over Mexico, the majority of them located in the traditional mine belt of colonial origin. This included Zacatecas, Guanajuato, Real de Catorce in San Luís Potosí,

[82] Federico Weidner, *El Cerro del Mercado de Durango. Compendio de noticias mineralógicas, orognósticas, históricas, estadísticas y metalúrgicas de dicho cerro y la Ferrería de San Francisco* (México: Imprenta de Andrade y Escalante, 1858), 30. The ironworks manufactured a maximum 3.6 metric tons of pig iron weekly by burning 23 metric tons of charcoal (or 115 metric tons of wood).

[83] Approximately five units of wood produced one unit of charcoal. The Lucas Alamán quote comes from Horacio Labastida, *Documentos para el estudio de la industrialización en México. 1837–1845* (México, D. F.: Secretaría de Hacienda y Crédito Público: Nacional Financiera, 1977), 34.

[84] This estimate follows Edward Wrigley's discussion of energy limits in "organic societies." "The heat output," writes Wrigley, "from the combustion of dry wood is 4,200 kcal/kg compared with 8,000 kcal/kg in the case of bituminous coal." Wrigley argues: "[i]f half the land surface of Britain had been covered with woodland; it would only have sufficed to produce perhaps 1 ¼ million tons of bar iron on a sustained-yield basis." See *Energy and the English Industrial Revolution*, 16. Estimates on wood consumption in nineteenth-century Mexican ironworks come from Labastida, *Documentos para el estudio de la industrialización en México, 1837–1845*, 221. For comparison, in 2015 and 2016 Mexico produced 7,581,577 and 6,969,582 metric tons of iron, respectively. See "Anuario Estadístico de la Minería Mexicana" (México, D. F.: Servicio Geológico Mexicano, 2017), 36.

the Pachuca area mines, and Taxco, in Guerrero. Most mines were relatively small, worked by about a dozen miners, and yielded modest outputs. Human and animal muscle provided mechanical energy and wood supplied heat. Technological inputs included simple tools and the ubiquitous horse-powered winch (*malacate*) for draining mines. A few mines, however, were large-scale operations with thousands of miners. These also used steam engines, which had a gargantuan appetite for fuel. Take the famous Real del Monte, a highly productive mine in Hidalgo, northeast of Mexico City.[85] In the 1820s, the mines came under the control of British investors, who sought to make them profitable again following the production collapse during the wars of independence. The British introduced some of the first steam engines in Mexico to drain flooded tunnels. In 1834 alone, Real del Monte in combination with one refining hacienda devoured a forest some seven times the area of Mexico City.[86] Charcoal consumption must have risen further when the company acquired a 400-horsepower steam engine in 1853, a veritable giant at the time.[87] Other major mining

85 Hidalgo state produced 2,400 metric tons of silver between 1667 and 1806, devouring 2,700 to 4,000 $km^2$ of forest. Silver figures come from Studnicki-Gizbert. Contrast with Guerrero, "The Environmental History of Silver Refining in New Spain and Mexico," 538. Guerrero's calculations are almost certainly too low. He assumes (p. 167) that 0.4 hectares of forest produced 1 ton of charcoal (18.5 $m^3$ (925 kg) of wood), and 1 ton of charcoal produced 1 kg of silver, while 1 hectare of forest produced 2.5 tons of charcoal. He then adopts a very low wood-to-charcoal conversion rate of 10 percent, meaning that 10 units of wood equaled 1 unit of charcoal (sometimes he uses a more typical 5:1 ratio). Based on these assumptions, Guerrero implicitly proposes an average annual wood growth of 25 tons per hectare, an exceptionally high figure only second-growth patches of tropical rainforest or some contemporary tree plantations can yield. It's unlikely that any temperate forest or dry woodland in the mining belt was so productive during the colonial period; the net primary productivity of Mexico's temperate forests today ranges between 5 and 10 tons per hectare. In other words, even when one uses a conversion of 5 units of wood for 1 of charcoal, Guerrero is still assuming 12.5 tons of wood per hectare, a productivity level above any temperate forest in Mexico today.

86 The steam engines required 34,204 metric tons of fuelwood (*leña*) – 57 $km^2$ of forest – while the refining hacienda (hacienda de beneficio) consumed 138 metric tons of charcoal weekly (7,176 metric tons annually), equaling 12 $km^2$ of forest. See Rafael de Armenta, "Consumo de leña en las minas de Real del Monte," *Boletín de la Sociedad Mexicana de Geografía y Estadística* II (1870 [1834]): 509. According to Real del Monte's own records, in a typical month in 1830, fuelwood represented 13 percent of the company's expenditures (including cutting and transportation costs), second only to piecework. See "Real del Monte Mining Company Expenditures and Returns" (April 7, 1830), José Villegas Collection on Mining. MSS 758. Special Collections & Archives, UC San Diego. By the late 1840s, Real del Monte faced serious fuelwood shortages. See Robert Randall, *Real del Monte: A British Silver Mining Venture* (Austin: University of Texas Press, 2014), 162–4.

87 Typical steam engines at the time delivered a few dozen horsepower. William Parish Robertson, *A Visit to Mexico, by the West India Islands, Yucatan and United States: With Observations and Adventures on the Way* (London: Simpkin, Marshall & Co., Stationers' Hall Court, 1853), 175. Robertson suggests that tree plantations existed on the mine's estate for fuel. In 1850, 41 censused mines worked in the State of Mexico, including Real del Monte, the largest, which consumed 10,027 metric tons of charcoal and 114,373 pesos of fuelwood (which, assuming a price of approximately

operations had similar fuel needs. The nearby Mineral del Chico, Hidalgo, consumed the yield of some 90 $km^2$ of forest in 1849 to fuel production.[88] Fresnillo, in Zacatecas, required 89 $km^2$ annually in the 1840s. Even relatively small operations like the mines of Anangueo, Michoacán, used almost 13 $km^2$ of forest annually.[89]

As more mines adopted steam engines, fuel consumption rose accordingly. Mexico's steam engines, like their British counterparts, were first used to drain flooded mines. It is possible a steam engine was operating in the mines of Real de Catorce as early as 1819. Santiago Smith Wilcox, the first US consul in Mexico City, obtained rights to import steam engines in 1821.[90] In 1823, one Juan Black imported one of these devices into Mexico for the Temascaltepec mine, west of Mexico City.[91] More reliable reports indicate that steam engines came to Real de Catorce between 1819 and 1823.[92] Whatever the exact date, it is clear that steam engines were introduced in Mexico only a handful of years later than in Peru, the first territory in Spanish America to use the technology.[93] With 40 horsepower, the Temascaltepec engine operated 8 pumps that drained 3,153 cubic meters of water every 24 hours. For comparison, a *malacate* could draw about 900

2.4 pesos per metric ton, was equivalent to 47,655 metric tons). Charcoal supplies alone required 88 $km^2$ of forest and fuelwood 79 $km^2$. The census data is in Sociedad Mexicana de Geografía y Estadística, *Boletín de La Sociedad Mexicana de Geografía y Estadística*, vol. II (México: Sociedad Mexicana de Geografía y Estadística, 1850), 247. The price estimate comes from data included in Juan Burkhart, "Memoria sobre la explotación de minas en los distritos de Pachuca y Real del Monte de México," *Anales de la Minería Mexicana* (1861): 106–7.

[88] If practice at Mineral El Chico was standard in mid-nineteenth-century Mexico, mines favored clear-cutting over sustainable wood harvest. At El Chico, "the wood to buttress the shafts and to make fuel is abundant, but it will disappear in a few years, as it already has in Pachuca, because the forests are cut without replanting a single tree for their reproduction." See Sociedad Mexicana de Geografía y Estadística, *Boletín de la Sociedad Mexicana de Geografía y Estadística*, II (1850): 264.

[89] Ibid., 267; 292–302; 318.

[90] Emilio del Castillo Negrete, *México en el siglo XIX, o sea su historia desde 1800 hasta la época presente* (México: Las Escalerillas, 1887), vol. 12, 465, claims that the Mexican government gave Willcox exclusive rights to import steam engines into the country (apparently, he never did). This privilege was later reversed over concerns that the monopoly might slow steam engine adoption across Mexico.

[91] "Máquina de vapor en el mineral de Temascaltepec, Estado de México," *El Sol*, August 6, 1824.

[92] Clara Bronstein, "La introducción de la máquina de vapor en México" (Tesis de Maestría, UNAM, 1965), 132–9. Strictly speaking, these were not Mexico's first steam engines (there seems to have been a model steam engine in the Palacio de Minería in the early nineteenth century.) See Bronstein, 94–5. Colonial authorities in the 1720s and 1730s tried and failed to introduce a Newcomen atmospheric engine to drain flooded mines. See Carlos Sempat Assadourian, "La bomba de fuego de Newcomen y otros artificios de desagüe: un intento de transferencia de tecnología inglesa a la minería novohispana, 1726–1731," *Historia Mexicana* 50, no. 3 (2001): 385–457.

[93] "Máquina de vapor en el mineral de Pasco, Perú," *Gaceta Extraordinaria del Gobierno de México*, April 16, 1817, tomo VIII, núm. 1059.

cubic meters within the same period.[94] Later reports from the 1830s and 1840s on the mines of Fresnillo, Zacatecas suggest that despite an enormous initial cost, sometimes running up to half a million pesos, a steam engine's operating cost could be less than half that of horse-powered *malacates*. Not to mention that steam engines could reach depths of 800 to 875 meters, far beyond the *malacate*'s reach.[95] But even a medium-sized machine like the Temascaltepec engine burned through 17 metric tons of wood daily, a rate that devoured some 10 $km^2$ of forest to keep running year-round.[96]

The enormous energy requirements of steam engines concerned many Mexicans during the first half of the nineteenth century. Some found them ill-suited to a fuel-poor country like Mexico, which had neither vast forests like the USA nor rich coal deposits like Great Britain. The renowned Spanish mining engineer Fausto de Elhuyar, founder and director of New Spain's College of Mines (*Colegio de Minería*) and longtime royal mine supervisor, adamantly opposed adopting steam engines in Mexico. When the Spanish crown consulted him in the early nineteenth century about a plan to introduce steam engines to revive New Spain's mining industry, Elhuyar rejected the idea on grounds that the country lacked enough fuel. He claimed that steam engines were unviable in Mexico due to lack of coal and widespread deforestation, especially around mining centers. He favored animal-powered *malacates* to drain mines; though not very efficient or applicable to deep mines, *malacates* were cheap and easy to use. Aware that his opposition might be overridden, Elhuyar emphasized the necessity of implementing forest conservation measures in case steam engines came to New Spain. He also called for locating coal deposits as soon as possible.[97] Elhuyar's proposition to conserve forests while simultaneously pushing coal as an alternative to wood would emerge time and again in similar discussions over the next century.

[94] F. J. Down, *Embracing a Sketch of the Most Thrilling Incidents in the History of Ancient Mexico and Her Wars, the Present State of the Country, and Its Mines; a Full Account of the War Between the United States and Mexico* (New York: 128 Nassau-Street, 1850), 96. In this case, twelve horses moved each *malacate*, likely in shifts to keep the *malacate* working night and day. As this mine needed several *malacates* operating simultaneously to keep the mines dry, it probably employed dozens if not hundreds of horses. These expensive animals frequently represented a substantial percentage of a mine's total operating cost.

[95] Sociedad Mexicana de Geografía y Estadística, *Boletín de la Sociedad Mexicana de Geografía y Estadística*, II: 292–302. Half of expenses went to cover the astronomical cost of transporting these machines overland by oxcart from the port of Veracruz to Fresnillo, over 1,000 km away.

[96] "Máquina de vapor en el mineral de Temascaltepec, Estado de México," *El Sol*, August 21, 1824.

[97] Bronstein, "La introducción de la máquina de vapor en México," 89–114. Elhuyar's opposition was maybe self-serving: he had recently invented (or improved) a water-powered machine that drained mines. Additionally, Elhuyar did not seem to know of Watt's much more fuel-efficient steam engine.

Fuel scarcity was not the only concern among steam's opponents. During the 1820s, steam engines were located in distant mines in the countryside, far from most urban residents. In the following decade, however, several factories and urban establishments began adopting these devices. Some town dwellers decried their presence, deeming them noisy and potentially dangerous. Angry residents of an urban neighborhood where a steam-powered textile factory was being built complained that

> in addition to [the steam engine] being very annoying to the people of this neighborhood due to the great noise it will make, which will certainly hurt one's ears whether one is on the same street or three blocks away, it is frightening because it has happened that engines blew up entire city blocks, killing everyone living there and some who were close by, as was the case up north.[98]

Their "just and rational fears" of steam engines seemed to have little sway with officials and industrialists, who viewed the machines as beacons of progress. In fact, the government granted privileges and tax exemptions to businessmen who introduced or invented new industrial technologies. One San Luis Potosí entrepreneur requested such prerogatives to establish a steam engine at a chocolate factory. The editors of the *Gaceta de San Luís* (the *San Luis Gazette*) opposed the businessman's request on the grounds that the steam engine, which had been imported from France, would economically devastate the large number of chocolate dealerships (*expendios*), not to mention the countless number of women who manually ground chocolate (*molenderas*).[99] Indeed, many poor people initially viewed steam engines as a threat to their very livelihoods. Beyond being noisy and dangerous, other critics claimed that steam engines could contaminate or taint food.[100]

Still, everybody seemed to agree these engines represented a turning point. For the first time in history, heat could be turned into motion. Under the solar energy regime, people viewed energy not as different manifestations of the same underlying reality but as a set of discrete sources.[101] With the invention of the steam engine (and later the internal

[98] "Vecinos se oponen a instalación de una fábrica textil movida por máquina de vapor," *El Mosquito Mexicano*, December 9, 1834.

[99] "Oposición a uso de máquina de vapor para hacer chocolate por afectar clases menesterosas," *El Cosmopolita*, September 11, 1839. *Molenderas* sometimes ground their chocolate at home and then brought it to customers. Other times, they ground chocolate at their customers' homes (usually wealthy patrons.)

[100] "Máquina de vapor para moler chocolate," *El Siglo Diez y Nueve*, September 23, 1842.

[101] Sieferle, *The Subterranean Forest*, chapter 1.

https://doi.org/10.1017/9781108923972.002 Published online by Cambridge University Press

combustion engine and electric motors and turbines), the gates that had previously cordoned off different energy forms were lifted. As scholars have pointed out, it is no coincidence that a unified concept of energy as a single entity converted into different forms only emerged after the creation of the steam engine, the first nonbiological converter.[102]

Aware of their enormous power, industries beyond mining began using steam engines in the 1840s. Textile factory owners were among the first converts. Both cotton and wool manufacturers employed them.[103] But steam remained an unlikely option, for it required an enormous financial investment. In places like Puebla, then the center of Mexico's textile industry with its abundant water resources, most industrialists in the 1840s continued privileging cheaper waterpower. Out of the 21 textile factories located in Puebla in 1843, 18 used waterpower while the remaining 3 employed mule-powered machinery.[104]

Despite cost and opposition, steam engines found various applications in Mexico. In 1843, engineers used steam engines to remove water from the foundations of the new dock at the port of Veracruz.[105] As early as the 1830s, some people in Mexico realized that these devices could be used in transportation. Likely, they had attended exhibitions demonstrating steam's versatility and potential. One such exhibition featured a steam-powered coach running on a small, circular track laid in the patio of a Mexico City building. For only two reales (a quarter of a peso), visitors could admire "one of the greatest inventions of human ingenuity."[106] Almost three decades before Mexicans successfully established a national railroad network in the late 1870s, a few steamships transported passengers and goods along Mexico's coast and even on the lakes and canals of the Valley of Mexico.[107] (Figure 1.2). Accounting for mines, factories, and a handful of steamboats, there may have been up to 100 steam engines in Mexico by the 1850s.

[102] Allen MacDuffie, *Victorian Literature, Energy, and the Ecological Imagination* (Cambridge, England: Cambridge University Press, 2014), part 1.

[103] "Máquina de vapor en el mineral de Plateros, Zacatecas," *El Registro Oficial. Periódico Oficial del Estado de Durango*, March 30, 1845; "Informe de D. Pedro de Baranda sobre la fábrica de tejidos de algodón que tiene establecida en el Distrito de Valladolid," *El Siglo Diez y Nueve*, August 22, 1844. Dirección General de la Industria Nacional, *Memoria sobre el estado de la agricultura e industria de la República en el año de 1844* (México: José M. Lara, 1845), 20.

[104] Estevan de Antuñano, "Estado de la industria manufacturera de algodones en Puebla, nacida en dicha ciudad el año de 1835," *El Siglo Diez y Nueve*, March 28, 1843.

[105] "Máquina de vapor para construir muelle en el puerto de Veracruz," *El Siglo Diez y Nueve*, June 6, 1843.

[106] "Exhibición de carruaje movido por máquina de vapor," *El Fénix de la Libertad*, October 18, 1833.

[107] "Navegación por vapor en el Canal de La Viga," *El Siglo Diez y Nueve*, May 15, 1849; "Navagación por vapor en el Valle de México," *El Siglo Diez y Nueve*, September 28, 1852. Steamboats continued operating on the valley's lakes until the 1890s.

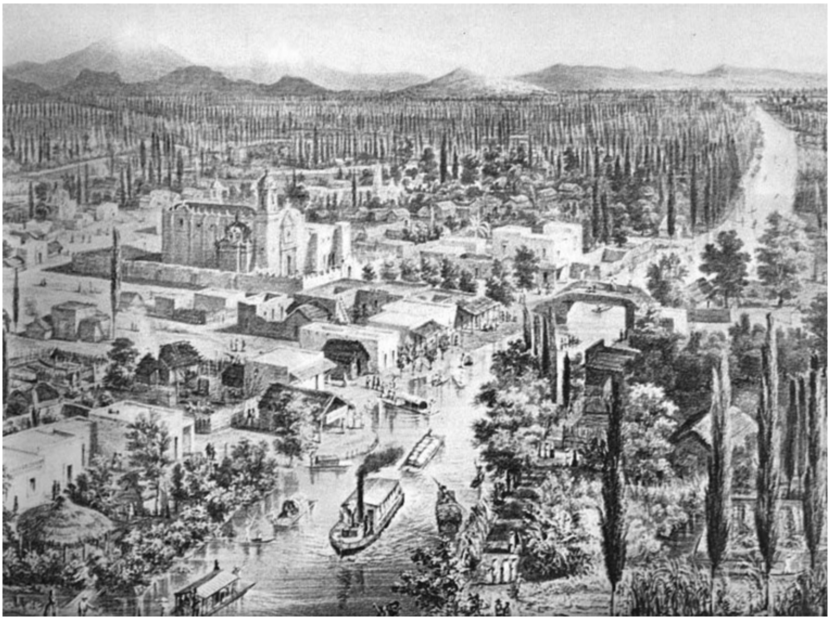

Figure 1.2 Steamboat *La Esperanza* on the Canal de la Viga. This canal connected the valley's southern lakes with Mexico City. The lithography was made from a balloon. Source: Manuel Arróniz, *Manual del viajero en Méjico*, 1858, 52.

Steam engines required heavy fuel inputs, putting further pressure on forests. How much fuel, then, did mid-nineteenth-century Mexico consume between wood and charcoal for all manufacturing and extractive purposes? The short answer is that we do not know. There were no reliable statistics for this type of consumption in mid-nineteenth-century Mexico. That said, we can use proxy figures to gauge the overall impact industry had on forests. The most accurate data is for all-important silver production. Between 1851 and 1860, Mexico produced a total of 4,569,500 kg of silver.[108] Silver production burned through a forest the size of the state of Tlaxcala every year and consumed the yield of a forest area larger than the state of Puebla in those 9 years.[109] After adding in ironworks, glassworks,

[108] Secretaría de Industria, Comercio y Trabajo, *Anuario de Estadística Minera* (México: Talleres Gráficos de la Nación, 1923), 42.

[109] Studnicki-Gizbert and Schechter, "The Environmental Dynamics of a Colonial Fuel-Rush." About 1,000 kg (1 metric ton) of charcoal produced 1 kg of pure silver. Assuming a ratio of five

and the many other industries that required heat energy in their productive process, there is no doubt this total figure would be substantially higher.

The combined pressure on Mexico's forests from traditional industries (iron) and new technologies (steam engines) inspired a growing interest in coal. As early as 1829, the state government of Nuevo León granted a concession to one Juan Woodbury and one Juan Cameron to exploit iron and coal deposits in the state. These individuals also obtained permits to import machinery, presumably steam engines for mines.[110] From the 1830s, newspapers reported coal deposits discovered across the country, emphasizing their significance by claiming that no other fuel was "more appropriate for the steam engines that are currently employed to drain mines."[111] Enthusiasm for coal came from the common view that coal would reduce dependence on Mexico's depleted forests[112] along with the conviction that Mexico required large quantities of coal to enter what industrialist Estevan de Antuñano called the "English stage" of industrialization.[113] Production needed investment, and investment depended on legislation. When, in 1841, General D. Vicente Filisola requested that the Mexican government grant him monopoly rights to exploit coal across Mexico for 10 years, a government-appointed committee refused. Members justified their decision on the grounds that coal was essential for "the progress of arts" (industry) and that England, the world's "leading manufacturing nation," never allowed coal monopolies in its territory.[114] This laissez-faire approach, however, failed to increase Mexico's coal production. By the late 1840s, the government decided to exempt imported coal from duties, a practice that would continue for decades.[115] By the early 1850s, coal was present in ironmaking and as a fuel for steam engines

units of wood per one unit of charcoal and an average productivity of 600 tons of wood for Mexican forests per $km^2$, the wood yield of 38,079 $km^2$ was harvested in those 9 years to produce Mexico's silver.

110 "Concesión a los ciudadanos Juan Lucio Wodbury y Juan Cameron para la explotación de minas de fierro y carbón de piedra" (October 4, 1829), Fondo: Capital del Estado; Sección: Reglamentos, decretos y circulares; Colección: Impresos II; Volumen: 6; Exp: 4, AHM.

111 "Descubrimiento de mina de carbón de piedra en Carácuaro, Michoacán y origen del carbón de tierra," *El Gladiador*, May 23, 1831. There is a reference to coal use in Guanajuato in 1805, which, if correct, would be the earliest in Mexico. See Sociedad Mexicana de Geografía y Estadística, *Boletín de la Sociedad Mexicana de Geografía y Estadística*, II: 27.

112 ". . . la explotación de minas de carbón [es] el único medio de acelerar la reparación de los bosques que han sido devastados." "Utilidad de las plantas," *El Mosaico Mexicano*, January 1, 1840.

113 Estevan de Antuñano, *Pensamientos para la regeneración industrial de México* (México, D. F., M. Porrúa, 1955 [1837]), 85–6.

114 "Petición de monopolio y extracción de carbón mineral," *Semanario de la Industria Mexicana*, June 15, 1841.

115 Mexican officials considered coal essential for locomotives. See Secretaría de Fomento, *Colección de leyes, decretos, disposiciones, resoluciones y documentos importantes sobre caminos de fierro, años de 1824 a 1870*, vol. 1 (México: Imprenta de Francisco Díaz de León, 1882), 32.

in mines and for the handful of steamboats that called at Mexican ports.[116] Overall consumption probably did not exceed a few thousand metric tons annually.

In sum, mid-nineteenth-century Mexico found itself in an unenviable situation. Centuries of silver mining, iron production, and agricultural expansion and animal husbandry (especially goat and sheepherding) had caused substantial deforestation, especially in the central highlands and the mining belt. The total forest area in the mid-nineteenth century was between 200,000 and 300,000 $km^2$, representing 10–15 percent of Mexico's territory. While several European countries featured territories with a mere 6 percent forest cover, Mexico's forested area was minuscule compared with that of the USA.[117] But Mexico seemed to have little coal to supplement wood, as opposed to European countries and the USA. Put simply, Mexico was attempting to develop its industry with relatively scarce wood supplies and little to no coal. Forests provided almost all the heat energy and an increasing share of mechanical energy for steam engines. Combined, domestic and industrial consumption probably exploited the annual yield of 10,000–15,000 $km^2$ of forest, or anywhere between 3 and 7.5 percent of the country's total forest area. While many peasant communities were forced to harvest wood on a more or less sustainable basis to maintain forest cover, between a third and a half of all Mexican forest was likely clear-cut. Most of the clear-cutting came from mines and factories, which could afford fuelwood transported from distant sources. There is little doubt that overall pressure on forests in mid-nineteenth-century Mexico was considerable and made other sources of energy attractive.

## Water and Wind

Water and wind were subordinate sources of energy in mid-nineteenth-century Mexico. While waterpower played an important role on land, wind power was rare. Waterwheels were common in haciendas and various workshops and factories, especially modern textile establishments. They milled grain, powered hammers in foundries and ironworks, and moved mechanical looms. Haciendas and ranchos used *norias* to irrigate land. Windmills were virtually nonexistent in Mexico, but wind worked at sea,

116 "Entradas al puerto de Acapulco. Importación de carbón inglés," *Periódico Oficial del Gobierno de los Estados Unidos Mexicanos*, April 21, 1852.

117 United States Department of Agriculture, "US Forest Resource Facts and Historical Trends" (Forest Service, August 2014), 7. In 1850, 45 percent of US territory was classified as forest.

where, with the exception of some steamboats, sailboats comprised the majority of the country's small merchant fleet.

Where was Mexico's water? Once again, geography was not kind to Mexicans. Most water was abundant where human population was not, particularly the southeastern tropical lowlands. Water scarcity marked the densely populated central highlands and the northern mining belt. Fifty-four percent of the country's runoff comes from just three rivers: the Grijalva-Usumacinta, the Papaloapan, and the Coatzacoalcos.[118] All three drain parts of the southeastern Mexican tropical lowlands. The biggest river system in central-western Mexico is the Lerma-Santiago, beginning in an area west of Mexico City and flowing into Lake Chapala, the country's largest freshwater lake, and the Pacific. This system traverses 58 basins and its total annual flow represents only 3.4 percent of the nation's water.[119] Great seasonal variations mean that most of this flow occurs during the rainy months between May and September.[120] In other words, the majority of Mexico's mid-nineteenth-century population, towns, and cities were located in a region characterized by mountainous terrain, numerous small basins, and relatively low-volume rivers that run high for just a few months of the year. The vast, semiarid region north of Mexico City was even less fortunate. Excluding the Sinaloa River and the Bravo-Conchos systems, rivers in the north were few and meandered across vast, largely empty desert landscapes.

These factors make it clear why the majority of the country's water-driven machinery was located in farms, mines, workshops, and factories in central, western, and north-central Mexico. They also explain why water was a relatively subordinate energy source, especially compared with western Europe and the eastern USA. Since medieval times, several European societies had relied on waterpower for a variety of tasks, including grain milling, wood sawing, and operating heavy hammers in foundries and workshops. As early as the eleventh century, there was 1 water-powered mill

[118] Mexico contains 37 hydrological regions with a total runoff of 378,311 $hm^3$ (cubic hectometers). Rivers and streams represent only 22.1 percent of the 1,489 billion $m^3$ of precipitation that falls in Mexico; 73.1 percent evaporates back into the atmosphere, and 4.8 percent percolates through soil and accumulates in underground aquifers. See Comisión Nacional del Agua, *Atlas del agua en México* (México, D. F.: CONAGUA, 2011), 22–8. A mid-nineteenth-century description of Mexico's rivers and lakes is Brantz Mayer, *Mexico, Aztec, Spanish and Republican: A Historical, Geographical, Political, Statistical and Social Account of That Country from the Period of the Invasion by the Spaniards to the Present Time, with a View of the Ancient Aztec Empire and Civilization, a Historical Sketch of the Late War, and Notices of New Mexico and California* (Hartford: S. Drake, 1852), book IV, 17–21.

[119] Comisíon Nacional del Agua, *Atlas del agua en México*, 22.

[120] In the Lerma-Santiago hydrological region, 64 percent of precipitation falls from July to September. Comisíon Nacional del Agua, *Atlas del agua en México*, 32.

for every 350 people in England. The three early nineteenth-century New England industrial centers, Lowell, Lawrence, and Manchester, derived their energy from the Merrimack river.[121] Places like Puebla, which had both a large population *and* water, were the closest Mexican equivalents and became industrial and manufacturing leaders in the 1830s and 1840s. The productivity of the state's numerous water-powered textile factories was unsurpassed in Mexico at the time.[122] But even in Puebla, most cloth was woven by hand using the 30,000 or so individual looms, also called *malacates*.[123]

Originally introduced by the Spanish soon after conquest, waterwheels became common in both Spanish and indigenous settlements.[124] Some early colonial mills employed undershot waterwheels, which move in the opposite direction to the running water. This model was relatively inefficient at harnessing the kinetic energy of water and required high-speed running water to operate properly. Depending on local conditions, other mills preferred horizontal waterwheels (*rodeznos*), which were technically simple (no complex gears) and needed only a small volume of water.[125] Another available model was the overshot wheel, the most efficient of which could convert up to 85 percent of water's kinetic energy to mechanical energy. Here, water was diverted from a river or stream into a channel or, typically, an aqueduct and then fed through flumes into buckets at great

[121] Smil, *Energy in World History*, 108; Smil, "World History and Energy."

[122] At *La Constancia Mexicana*, the state's largest and first mechanized textile establishment in Mexico, 113 water-driven looms churned out 600 pieces of cloth weekly (312,000 annually), enough to clothe about 15 percent of the state's 660,000 inhabitants in the 1840s. These power looms were about six times more productive than a person. Data on La Constancia comes from Antuñano, "Estado de la industria manufacturera de algodones en Puebla, nacida en dicha ciudad el año de 1835." Puebla's estimated population in the 1840s is in INEGI, *Estadísticas históricas de México: Población* (Aguascalientes: INEGI, 2008), 102. A piece of cloth (*pieza de manta*) typically measured one *vara* (0.8 meters); an average Pueblan in the 1840s needed three per year. A weaver and an assistant produced two pieces of *manta* weekly, a third of a water-powered loom's production. See Jan Bazant, "Industria algodonera poblana de 1803-1843 en números," *Historia Mexicana* 14, no. 1 (1964): 131–43.

[123] Estevan de Antuñano, "Documentos para la historia de la industria algodonera de México, en lo fabril y en lo agrícola, o sea narraciones y cálculos estadísticos sobre ella," *El Siglo Diez y Nueve*, March 28, 1843.

[124] On the colonial history of waterwheels, see Magdalena García, "El dominio de las 'aguas ocultas y descubiertas': hidráulica colonial en el centro de México, siglos XVI-XVII," in *Mestizajes tecnológicos y cambios culturales en México* (México, D. F.: CIESAS; Miguel Ángel Porrúa, 2004), 93–128. The oldest waterwheel reference dates back to the first century BCE in the eastern Mediterranean, though the technology was likely much older. See Smil, *Energy in World History*, 103, and Terry S. Reynolds, *Stronger than a Hundred Men: A History of the Vertical Water Wheel* (Baltimore: Johns Hopkins University Press, 1983).

[125] Víctor Gómez, "Los molinos del Valle de México. Innovaciones tecnológicas y tradicionalismo (Siglos XVI–XIX)" (PhD Dissertation, UAM-Iztapalapa, 2008), 161–4.

speed. Since the wheel's movement was generated by the weight of the water, overshot wheels could be located on slow-flowing rivers, greatly expanding their range and applications.

In Mexican haciendas and pueblos, the waterwheel was used for milling wheat (not maize). One Hacienda de los Hornos in Chihuahua, owned by Don Leonardo Zuloaga, had a water-powered mill with an overshot waterwheel and two grindstones that could grind 2.7 metric tons of wheat every 24 hours. The water was carried into a canal – presumably from a storage pond, reservoir, or spring that ensured a reliable water supply – and fell from a height of 2.4 to 2.7 meters, filling the buckets and moving the wheel downwards.[126] Wheels like this probably delivered some 15 to 25 horsepower, if 1880s reports are any indication.[127] This was modest compared with later wheat mills. If it operated year-round without interruption (unlikely), the Zuloaga mill would produce 985.5 metric tons of wheat compared with the 5,000 metric tons of wheat that an enormous, electric 500-horsepower mill in Sonora could grind in a year by the early twentieth century.[128] Waterwheels in mid-nineteenth-century Mexico were commonly wood, given the paucity of iron in Mexico.[129] It seems that craftsmen preferred mesquite for its durability and ubiquity in Mexico's arid plateaus and highlands.[130] Less iron also forced craftsmen to rely on nonmetals for watermill parts, including the runner stones, which were kept in place with tight leather strips, much to the amazement of foreign observers.[131]

In industry, waterwheels powered looms and various types of machines that beat, crushed, ground, and sawed cloth, leather, ores, wood, and many other materials. We already mentioned water's role in the mechanized and modern textile industry that expanded in central Mexico between the 1830s and the 1850s. In general, the trend was a transition from muscle power

[126] "Un nuevo molino de agua en Chihuahua," *El Museo Mexicano*, January 1, 1844.

[127] *Memoria de la Secretaría de Fomento* (México: Oficina Tipográfica de la Secretaría de Fomento, 1887), vol. 5, 475–9. The three waterwheels in this description were located in the northeastern state of Tamaulipas on sugarcane haciendas. All were overshot wheels 5.7–6.50 meters in diameter, moved by 230–448 liters of water per second, falling from 6 meters and producing 15–24 horsepower.

[128] Gómez, "Los molinos del Valle de México," 192.

[129] Some industrial and agricultural enterprises refused to purchase iron-made machinery for fear of being unable to replace broken parts. See Severo Cosío, "Fundería de fierro en las minas de Proaño, Aguascalientes," *El Siglo Diez y Nueve*, April 21, 1856.

[130] By mid-century, wholly iron-made waterwheels were available in Mexico, advertised as "modern" over their "primitive" wooden predecessors. See "Para los industriales, dueños de trapiches, molinos a la moderna," *El Siglo Diez y Nueve*, October 27, 1852.

[131] Gómez, "Los molinos del Valle de México," 165.

(human and animal) to waterpower. Consider the mountainous, water-rich area southwest of Mexico City. Traditionally a fruit-producing area, the foothills became the locus of an incipient industrial corridor by the mid-nineteenth century. Scattered throughout the Valley of Mexico, most manufacturing establishments were located in the southwest, particularly along rivers. Heavy rainfall during the rainy season, sometimes three times as much as in the valley's drier northern areas, meant an abundant supply of water. Water-powered machinery quickly became widespread in the region. Out of 17 textile factories established here in the early 1840s, 8 were powered by human muscle, 5 by water, 2 by mules, and 1 by steam. A decade later, most of these factories used water. Waterpower led to increased factory size and productivity over time. In 1843, La Magdalena, one of the region's biggest textile factories, had 8,400 spindles and 90 water-powered mechanical looms (*telares de poder*), producing under 9,000 cotton cloth pieces a year. A decade later, La Magdalena increased its number of spindles to 8,472, but now had 326 mechanical looms. As a result, production skyrocketed to over half a million pieces of cotton cloth annually.[132]

Waterpower production capacity had limits. The Valley of Mexico's clear division between rainy and dry seasons produced enormous variations in the water volume that rivers and streams carried downhill throughout the year. It was common for mills to stop working altogether for extended periods. Some factory owners tried solving this problem by building reservoirs, which often caused conflict with local inhabitants who used water for irrigation and domestic consumption.

Despite these drawbacks, water's relative cheapness as an energy source and the familiarity of Mexican craftsmen with waterwheels and milling technology (as opposed to, say, steam engines), made waterpower highly attractive to certain users. Gunpowder factories, for example, were still relying on waterwheels by the mid-nineteenth century, and some of these became increasingly large, powerful, and

[132] Secretaría de Fomento, *Anales del Ministerio de Fomento, Indústria, Agrícola, Minera, Fabril, Manufacturera y Comercial, y estadística general de la República Mexicana* (Mexico: Impr. de F. Escalante y Comp., 1854), vol. 1, 6. Early 1840s data are in Labastida, *Documentos para el estudio de la industrialización en México,* 81. On La Magdalena and other textile mills in the Valley's southwest, see Mario Camarena Ocampo, "Fábricas, naturaleza y sociedad en San Ángel (1850–1910)" and Mario Trujillo Bolio, "Producción fabril y medio ambiente en las inmediaciones del Valle de México, 1850–1880," in Alejandro Tortolero, ed., *Tierra, agua y bosques: historia y ambiente en el México central* (Ciudad de México; Guadalajara, Jalisco, México: Centre français d'études mexicaines et centraméricaines: Instituto de Investigaciones Dr. José María Luis Mora: Potrerillos Editores; Universidad de Guadalajara, 1996).

complex.[133] One wheel installed in an undefined location in the 1820s powered two gears that moved four large, bronze cones each weighing over half a ton. These cones rotated on a platform crossed by a canal holding charcoal, saltpeter, and sulfur. Grooves surrounded the cones into which the ground paste flowed. A skilled worker then added water to moisten the mixture, a critical step that determined the final quality of the gunpowder. This water-powered gunpowder mill could grind the paste in 6 hours, a tremendous gain over the 24 hours required using muscle power. It also seems to have improved the quality and potency of the gunpowder and reduced human labor by three-fourths, highly appealing from the factory owner's perspective.[134]

In industry, waterpower and animal power were inversely proportional: the more abundant water was, the less likely it was that a mine or factory would rely on animal-driven machinery. The famous German writer Carl Sartorius, who spent most of his adult life in Mexico, confirmed this when he visited the foundries that processed ore from the Fresnillo mines, in Zacatecas. "These immense works [foundries]" – Sartorius wrote – "employ thousands of men and thousands of beasts of draft and burden because all the machines, due to the lack of water, must be set in motion by mules. This remark applies specifically to Zacatecas and its environs, for other areas, although not all, have waterpower."[135]

Perhaps windmills could have solved this quandary, but this ancient technology was nearly absent in Mexico.[136] Geography and environmental conditions were partly to blame. Although Mexico has substantial inland wind resources, most of them are concentrated in present-day Oaxaca, in the southeast.[137] Here, the Isthmus of Tehuantepec, Mexico's narrow waist separating the Gulf of Mexico from the Pacific by just 220 km, creates an enormous wind funnel. Warm marine currents in the Gulf of Mexico produce differences in temperature and pressure, generating constant

[133] Yolanda Terán Trillo, "Maderos impelidos por la fuerza del agua. Molinos del periodo virreinal," *Boletín de Monumentos Históricos*, núm. 27 (May 1, 2013): 99–110.

[134] "Rueda hidráulica en fábrica de pólvora," *El Sol*, November 15, 1825.

[135] Carl Christian Sartorius, *Mexiko. Landschaftsbilder and Skizzen aus dem Volksleben* (Darmstadt: Gustav Georg Lange Verlag, 1859), 345.

[136] On the windmill's history see Adam Lucas, *Wind, Water, Work: Ancient And Medieval Milling Technology* (Leiden; Boston: BRILL, 2006), 101–3. As late as 1903, Mexican windmills were imported from countries like the USA. See *Directorio general de la República Mexicana* (México: Ruhland & Ahlschier, 1903), 504.

[137] Present-day estimates place the total at about 40,000 to 60,000 MW, 35,000 of which may be in the Isthmus alone. See Mercedes Canseco, "Energías renovables en América Latina" (Madrid: Fundación Ciudadanía y Valores, 2010), 7; Sergio Romero, et al., "Energy in Mexico: Policy and Technologies for a Sustainable Future," 194.

strong wind from October to April.[138] The Isthmus, however, lacked a strong manufacturing or mining tradition and had few inhabitants in 1850. But unlucky geography cannot be the whole explanation, because Zacatecas is also among the best endowed with wind resources in the country.[139] So why didn't mining exploit this energy source using windmills? Perhaps people were simply unfamiliar with the technology or its applications. Or if they knew it, they maybe associated it with draining waterlogged or marshy soils to create farmland, not a problem in arid Zacatecas. Perhaps windmill intermittency discouraged industries that required machinery to operate without interruptions.

Whatever the reasons, wind was only used as an energy source along the coasts of Mexico. In 1852, of the 839 ships that called at Mexican ports, 73 percent were sailboats (frigates, brigantines, and schooners) and 27 percent used steam. Only 8 percent were Mexican, while 52 percent sailed under the American flag, followed by the English (13 percent) and French banners (8 percent).[140]

In sum, while water was a relatively minor power source compared with muscle and wood, it played important roles in farming and manufacturing in Mexico by mid-century. Waterwheels and new water turbines transformed the kinetic energy of running or falling water into mechanical energy for textile looms, hammers, grindstones, factories, mines, wheat mills, and various types of workshops across the country. Like other technologies, water-driven machinery was concentrated in areas with the largest population and human economic activity, particularly the central highlands and the mining belt in the center-north. Wind was of negligible relevance on land but powered most of Mexico's small naval fleet.

## Transport

Like other societies under the solar energy regime, mid-nineteenth-century Mexico faced a "transportation problem."[141] Overland transportation confronted clear energy limits, dependent as it was on muscle. Costs became prohibitive for many enterprises after a relatively short distance, especially

[138] Jorge Gutiérrez, "Energía renovable en el siglo XXI" (Monterrey, México: Senado de la República, 2001), 71.

[139] Q. Hernández-Escobedo, F. Manzano-Agugliaro, and A. Zapata-Sierra, "The Wind Power of Mexico," *Renewable and Sustainable Energy Reviews* 14, no. 9 (2010): 2830–40.

[140] Juan Nepomuceno Almonte, *Guía de forasteros y repertorio de conocimientos útiles* (México, 1852), 558.

[141] Sieferle, *The Subterranean Forest*, 57.

bulky, low-cost goods like grain and wood.[142] A pack of mules covered 20 to 30 kilometers daily, and in the highlands it cost 12–14 cents to transport one load (*carga*) of 138 kilograms (12 *arrobas*) 4 kilometers (1 *legua*), or 3.5 cents per kilometer. Thus, transportation costs for daily necessities like firewood (38 cents per *carga*) exceeded the item's price after 10–15 kilometers. Similarly, it only took a few dozen kilometers before items like grain and wood required more energy to haul than they contained. Only high-priced, low-volume goods like precious metals and luxury commodities remained profitable after long-distance transportation.[143]

Poor road conditions exacerbated the energy constraints of muscle-based land transportation. The main colonial roads from Veracruz to Mexico City and the one linking the latter city with Santa Fe, New Mexico fell into disrepair after decades of neglect. Other regions, including parts of the all-important northern mining belt, relied on poor-quality roads largely used by mule trains, horseback riders, or foot travelers – hardly fit for carts or coaches. On May 22, 1822, English engineer Robert Phillips and a Mexican colonel named Martínez departed from the port of Altamira, in Tamaulipas, with 14 four-wheel, ox-drawn wagons loaded with parts for a 36-inch steam engine. Their destination? The mine in La Concepción, Real de Catorce. After taking the only road north through Saltillo before veering south, the party covered some 800 km to arrive in Real de Catorce on November 11, almost 6 months later. The travelers braved high temperatures, broken wheels, and water scarcity. Most stretches of road were in bad shape. At points, the roads became narrow passages carved into mountainsides. Other times, the party hauled the machinery over rivers, at one point requiring the assistance of fifty Indigenous Mexicans and twenty yokes of oxen, and constructing a provisional dam to slow water flow. The terrain shattered wheels, and impromptu forges were built to mend them,

[142] Pérez Hernández, *Estadística de la República Mejicana,* 40–1. A *carga* or mule load was a measure of the weight one mule could carry. By comparison, it cost only 7–8 pesos to transport 1 ton of cargo from Panama to Acapulco, or from Acapulco to San Francisco. On a straight line, the distance from Panama to Acapulco is 3,000 km. Thus, it cost 7–8 pesos to transport 1,000 kg of cargo over 3,000 km by water. Hauling the same cargo overland would cost 756 pesos.

[143] This partly explains silver's preeminent economic role in New Spain and independent Mexico. It also underlines the enormous geographical obstacles Mexico faced when it began industrializing. Poor transportation and rugged topography became standard explanations for Mexican *atraso* (backwardness): John H. Coatsworth, "Obstacles to Economic Growth in Nineteenth-Century México," *The American Historical Review* 83, no. 1 (1978): 80–100. Missing in this argument is the acknowledgement that Mexico's "transportation problem" was typical of any society under the solar energy regime, which in the mid-nineteenth century included the entire world with the exception of regions with coal-based railroad transportation in Europe and the eastern USA.

contributing to delays. When the party finally arrived at their destination, they found the machinery badly damaged from travel. Phillips spent another 2 years making repairs before testing it, only to learn it needed iron pumps from the USA and another voyage to retrieve them. The steam engine finally began draining the mine in late November 1826, four and a half years after the initial trip.[144]

As English diplomat H. G. Ward pointed out, the condition of Mexico's roads rendered wheat grown in the highlands an "article of luxury" to residents of the port of Veracruz: "For strange as the assertion may appear, in the present state of the roads it would be easier, and cheaper, for towns upon the Eastern and Western coasts to draw their supplies from the United States, or California, by sea, than from the nearest corn lands on the tableland."[145] It cost half the price to ship wheat from Ohio to Veracruz than to import it from the wheat haciendas of Atlixco, Puebla, 300 km away (Table 1.3).

Unfortunately for Mexico, the country had few navigable rivers, and most could only be cruised by boats and ships with a small draft. The only rivers capable of carrying large ships flowed through the scantily populated tropical lowlands.[146] The exception was the Valley of Mexico. Here, the movement of people and goods depended on water transportation in the bottomlands, where large canoes crisscrossed the lakes and canals linking

Table 1.3 *Estimate of cost of cargo transport by land and water in Mexico, 1862*

| Type of Transport | Weight (metric tons) | Distance (km) | Cost |
|---|---|---|---|
| Overland (Mule) | 1 | 100 | 21.70 pesos |
| Water | 1 | 100 | 27 cents |

*Source:* José María Pérez Hernández, *Estadística de la República Mexicana*, 1862, 40–1.

[144] H. G. Ward, *Mexico in 1827* (London: Henry Colburn, 1828), 528–47. Tellingly, Phillips's trip to Cincinnati on the Mississippi River only took a little over 2 weeks.

[145] Ward, 47. "Corn" was generic for grain.

[146] Fewer than a third of Mexico's rivers were navigable by small ships. Pérez Hernández, *Estadística de la República Mejicana*, 24. A few steamers operated on the Pánuco River and along the Veracruz coast. See Miguel Lerdo de Tejada, *Cuadro sinóptico de la Republica Mexicana en 1856, formado en vista de los últimos datos oficiales y otras noticias fidedignas* (México: Imprenta de Ignacio Cumplido, 1856), 62–4.

Mexico City with its hinterland.[147] Lakes and canals made accessing urban consumers easy and cheap. The lake system represented essential transport until the late nineteenth century, when most of it was finally drained. Only after the arrival of railroads later in the century would water cease to be the valley's cheapest option for transport.[148]

## Conclusion

For millennia, societies inhabiting present-day Mexico lived under the solar energy regime. These societies depended predominantly on the solar energy stored in plants. This presented limits to population sizes and their capacity to transform the environment. That said, the region's history from pre-Hispanic times until the middle of the nineteenth century was highly eventful from an environmental standpoint. There were phases of intense modification followed by recovery periods, and moments of acute exploitation and irreparable damage followed by permanent abandonment. In the absence of draft animals, Mesoamerican indigenous civilizations developed complex societies powered by human muscle. Humans were the main energy converters of chemical energy stored in plants into mechanical energy.

Then came the Columbian Exchange with the introduction of livestock and diseases from the Old World. New pathogens wiped out most of the indigenous population and set the stage for the emergence of New Spain, with a heartland around Mexico City and a northern area centered around the Bajío and mining provinces. The former became a society of peasant communities with substantial ecological and food autonomy, commercial estates, and urban centers that channeled silver wealth into the global economy. The latter formed a highly commercial, manufacturing, capitalist economy organized around silver extraction,

[147] There were 81,217 canoes in 1861. See Hernández Pérez, *Estadística de la República Mejicana*, 171.

[148] Estimates for transport costs in preindustrial Europe are in Sieferle, *The Subterranean Forest*, 2001, 59. According to Pérez Hernández, a railroad from Mexico City to the villa de Guadalupe (4 kilometers) already existed in the early 1860s. A second linked Mexico City and Tacubaya (6 kilometers). The railroad from Mexico City to Veracruz was 26.4 km, although only one-third of tracks were operational. Within Mexico City, there were 640 carretas and 366 carretones for freight transport. Horses could also be rented for 5 pesos a day. There were 419 rental horses in the early 1860s. See *Estadística de la República Mejicana*, 37, 42. The figures for Mexico City's *cargadores* by the mid-nineteenth century are in Jesús Hermosa, *Manual de geografía y estadística de la República Mejicana*, 186. Perhaps not coincidentally, the valley's lake drainage project was finally accomplished – after almost 300 years of effort – only after railroads were introduced, a connection the literature on this topic overlooks. This suggests that an energy perspective may shed new light on even thoroughly studied topics such as the draining of the Valley of Mexico's lakes.

which deforested much of the region. Livestock expanded the limits of New Spain's solar energy regime, replacing humans in many tasks that required high energy expenditure. Then came waterpower, first introduced under Spanish rule, which increased the amount of energy available for manufacturing. After the silver economy collapsed with popular insurgency in 1810, Mexico's elites began promoting an incipient water-and-muscle-based industrialization process in parts of the country in the 1830s – radically early by global standards. The loss of vast northern territories to an expanding USA severely diminished Mexico's energy resources after 1848.

Mexico entered the 1850s with a less commercial economy, a shrunken territory, limited energy resources, and reliance on food energy and muscle power. That said, it was successfully developing a mechanized textile industry, reviving its mining sector, and amassing steam engines. First introduced in the 1820s to drain flooded mines, these devices made it possible for the first time to transform heat into motion. But the vast majority of these machines in Mexico used wood as fuel. Unlike, say, Britain, where they burned coal, steam engines in Mexico continued to depend on the amount of biomass available at any given location. Steam engines remained tied to local environmental conditions, operating under the constraints of the solar energy regime. This basic fact held enormous implications over the following decades as steam engine use in Mexico boomed with increased industrialization and the rapid expansion of the country's railroad system in the 1870s and 1880s. This multiplied the effect on Mexico's forests, depleted over centuries of silver mining. Forests began shrinking perceptibly in many regions, raising concern among state officials and industrialists over Mexico's long-term industrial potential.

The environmental, energy, and social conditions of the mid-nineteenth century emerged from the complex conditions of Mexico's previous centuries, which would deeply shape Mexico's energy history moving forward. To paraphrase that famous Marxist dictum, people in Mexico would make their own history, but not under the environmental and energy conditions of their choosing.[149] At the same time, changes in the types of energy exploited and the manner of their use would dramatically transform those initial circumstances.

[149] John R. McNeill, Something New Under the Sun: An Environmental History of the Twentieth-Century World (New York: W. W. Norton & Company, Inc., 2000), 194.