Historical Methods: A Journal of Quantitative and Interdisciplinary History

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/vhim20

Estimating energy flows in the long run: Agriculture in the United States, 1800–2020

Robert Suits & Elisabeth Moyer

To cite this article: Robert Suits & Elisabeth Moyer (31 Oct 2024): Estimating energy flows in the long run: Agriculture in the United States, 1800–2020, Historical Methods: A Journal of Quantitative and Interdisciplinary History, DOI: 10.1080/01615440.2024.2375714

To link to this article: https://doi.org/10.1080/01615440.2024.2375714

HISTORICAL METHODS: A JOURNAL OF QUANTITATIVE AND INTERDISCIPLINARY HISTORY
https://doi.org/10.1080/01615440.2024.2375714

Routledge
Taylor & Francis Group

Estimating energy flows in the long run: Agriculture in the United States, 1800–2020

Robert Suits[a] and Elisabeth Moyer[b]

[a]History, The University of Edinburgh School of History Classics and Archaeology; [b]Geosciences, The University of Chicago

ABSTRACT

This article explores the methods of a prior larger research project to understand flows in the US energy economy, quantifying energy use across American history (1800–2020). As a case study, it uses a subset of this data—agricultural energy use—to examine the methods, sources, and problems around estimating the production and consumption of energy at a national level. By combining statistical data with primary sources (like government and private studies on livestock feed demands), we produce a database that sums all energy used both on-field and in the processing and production of food more generally—and offer several counterintuitive conclusions. Per-capita agricultural energy use actually fell between 1800 and 2020. During this time period, the overall per-capita energy expenditure on food (in processing and cooking) remained fairly steady. We conclude the article by noting various uses for the data in reframing long-term agricultural trends and their environmental impacts. Energy flows are a fundamental component of social metabolism research. What this paper adds to this work is an unusual American case, one in which per capita on-field energy use declined.

KEYWORDS

Energy; agriculture; United States

Energy is the closest thing we have to a single factor that enables human society. It underlies economies, both preindustrial and industrial. Whether in the form of electricity or fossil fuels, energy consumption is tightly correlated with wealth across space and time; the economic growth of the last two centuries is founded on a massive expansion in global per capita energy consumption (Gales et al. 2007). This paper explores the creation of a database for U.S. energy history through a deep dive into a subset of this data. While in our larger project we compare energy consumption across sectors of the U.S. economy, here we focus exclusively on agricultural energy use. We cover our use of primary sources, which range from government statistics to aggregated historical scientific studies of agricultural energy use. We also compare our methods and conclusions to work in the wider field, and highlight the United States' unique energy history—particularly remarkable in the case of agriculture.

As the availability and nature of sources changed dramatically across the adoption of fossil fuels, long-term estimates of energy use are both extremely valuable and extremely difficult to do (Beltran 2018; Massard-Guilbaud 2018; Pallua 2018). Though foundational texts in energy history often aimed for large-scale estimates, many more recent studies in energy history instead focus on a single fuel, a single transition, or a single end use (like an engine type or lighting) (Braudel 1981; Chatterjee 2020; Cipolla 1961; Demuth 2019; Eaglin 2022; Montaño 2021; Seow 2022; Sieferle 2001). A few energy historians have tabulated the quantitative energy history of several countries; most notably, the work of Astrid Kander, Paul Warde, and Paolo Malanima assembling energy statistics across European countries, and Roger Fouquet's work on the United States since 1900 (Ayres et al. 2003; Etemad and Luciani 1991; H. Fouquet 2008; R. Fouquet 2010; R. Fouquet and Pearson 1998; Kander, Malanima, and Warde 2013; Mitchell 2007; O'Connor and Cleveland 2014; Schurr and Netschert 1960; Stercke 2017; Unger and Thistle 2013). These are, however, mostly exceptions.

Our dataset builds on this excellent work across multiple fields to offer a view of both "primary energy" as well as the "final energy" consumed in each sector of the economy. Primary energy refers to energy before any transformations—e.g., crude oil or coal; final energy to the energy consumed after these transformations have been applied—e.g., gasoline in one's automobile.[1] Tracking primary energy allows us to understand the energy system holistically.

CONTACT Robert Suits rmsuits12@gmail.com History, The University of Edinburgh School of History Classics and Archaeology, Edinburgh, UK.
Supplemental data for this article can be accessed online at https://doi.org/10.1080/01615440.2024.2375714.

While quantitative estimates are relatively sparse in recent energy history, there is a wealth of recent efforts in social metabolism research. Most of these study agricultural systems and their interaction with ecosystems across pre-fossil and fossil fuel eras (Krausmann and Haberl 2002). Of particular note, a 2018 special issue explored the circulation of energy within several agricultural systems (Soto et al. 2016). Across countries, they noted similar shifts toward increasing fossil fuel inputs into agriculture, increasing fluxes of energy per unit land area, an increasing proportion of net primary productivity going toward human use, and increasing agricultural production per laborer. Our own estimates differ somewhat in approach, owing to the demands of a larger analysis of the American energy economy, which are best served by per capita units. Moreover, we find that while the American experience reflects several wider trends—including the limited impact of human labor as an energy carrier—it is ultimately extremely unusual in its high early energy use.

This paper summarizes our general method. The most challenging estimates to construct concerned matters historical actors deemed unimportant. Though the United States' energy economy is extremely well-documented (with a sophisticated bureaucracy right from its founding), the statistical coverage of non-commoditized energy is laughably sparse. Fuel used in household stoves and fodder for horses and cattle were almost wholly ignored. The switch from one fuel to another, particularly early in an energy transition, tended to be poorly documented.

To illustrate these challenges, this paper takes as a case study our estimates of the agricultural sector. Most long-range estimates of American national energy use are not broken down by sector; those which do not treat agriculture separately.[2] This is in spite of the fact that agriculture comprised the most valuable part of the American economy across most of the nineteenth century, and is one of the most contested parts of green transition debates today. It is implicated in up to a quarter of global greenhouse gas emissions, depending on the metric used (Ritchie 2019). This leads to the common conclusion that industrialized agriculture is particularly unsustainable. But without reliable long-term historical estimates, this conclusion is pure speculation.

Our own estimates are particularly concerned with questions of energy intensity. This is defined as GDP divided by energy use; put another way, an energy intensive economy is "inefficient," requiring more energy to create the same amount of wealth. The United States is notoriously energy intensive, surpassing the energy consumption of most comparably wealthy economies in the G7 or OECD; this problem gets considerably worse as one goes further back in time. A particularly useful measure for thinking about the energy requirements of an economy is per capita energy consumption—our estimates are displayed in Watts/capita (as Watts are the SI standard for power, time-independent, and produce more intuitive values than comparable measures like MJ/year). These are sometimes used in estimates of agricultural energy, but not exclusively (other common units are energy inputs or outputs per unit area); across the whole economy, per capita metrics are extremely useful for understanding what kinds of living standards are possible with certain levels of energy consumption.[3] Moreover, they highlight some startling trends in American energy use.

Over the course of constructing our larger dataset, we discovered that despite its extensive use of fossil technology, modern American agriculture is not particularly energy inefficient. Measured by on-field power (i.e., tractors, horse drawn plows, etc.), it is relatively *more* energy efficient than it has ever been. On a per person basis, twenty-first century agriculture uses less energy to feed Americans than did nineteenth century American agriculture. Even the *total* of on-field power used in agriculture has remained little changed since 1900. This expanded dataset shows this is not an artifact of how we defined "agriculture:" on a per capita basis, the energy used even in the broader "food system"—our term for the industries that process and transform agricultural outputs into edible calories—has changed very little over time. Still more surprising, rough estimates of total livestock feed (not used for power, but rather in cattle or other food production) indicate they have not increased on a per capita basis, either. Americans today devote an enormous quantity of energy to feeding cattle, hogs, and chickens, but on a per capita basis, this was equally true since at least 1840.

This article begins by surveying the methods and sources of this project in more detail. It then proceeds to overview in brief specific components of the overall estimates, beginning with on-field agricultural power—everything physically taking place on a farm. It then explores the food system more widely. Although we do not devote much space to conclusions, the upshot of this data is even including all of these processes and animal feed data, twenty-first century American agriculture is not unprecedentedly energy intensive. Rather, American agriculture has *always* been extremely energy intensive. If we are to truly grapple with these issues, it must be with some awareness that the problem has far deeper roots than are usually acknowledged.

Methods, sources, problems

The end goal here appears simple: measure all energy used across American history. But most historians reading this will know of deeply flawed quantitative historical projects. Historical quantitative estimates, especially large-scale ones, can struggle for reasons ranging from ignoring how data was created in the first place, to ignoring how concepts and material objects can change over time. On the other hand, the assumption that this data is either completely unrecoverable or unquantifiable is simply incorrect. In this section, we will detail our source base and then our approach, not only to underline what was challenging and unique about the creation of this dataset, but also to encourage more works like this one. The pace and shape of agricultural energy transitions illuminates both historical energy use—and the possible shape of contemporary energy transitions as well.

Overall, our study can be chronologically split into three groups of sources spanning different eras of record-keeping and economic structures. Recent government energy data is excellent, closely tracked by the government, and highly differentiated between different sectors. Statistics on fuels and electricity use, the embodied energy in fertilizers and pesticides, and farm animal size are all widely available. In the early twentieth century, some of this data is available, most statistics instead prioritize figures like head of livestock, number of tractors, or farm capital and acreage. In the nineteenth century, even these statistics grow somewhat inconsistent. Fortunately, scientific studies (both private and government) of livestock span all three eras, allowing a close study of the evolution of animal power over time. The goal of the project in creating a dataset spanning these eras was to find ways to estimate energy using these available statistics.

Energy is closely tracked in the modern economy, and agriculture is no exception. The best source of American energy data since 1949 is the Energy Information Administration's monthly reports (Energy Information Administration 2022a). The EIA does not, however, separate agricultural energy, even in its more detailed reporting. Instead, this information can be found in the National Agriculture Statistics Service's triennial surveys showing the amount of a given fuel burned by farmers in their operations, as well as electricity consumed; this has been produced since 1965 (National Agricultural Statistical Service Homepage 2022). Prior to this point, the Census Bureau sampled agricultural gasoline consumption for a narrow sliver of time between 1940 and 1954, well after the introduction of tractors.[4] As the energy content of the principal agricultural fuels (gasoline, diesel, and natural gas) is relatively unvarying, it is easy to convert the use of these fuels to figures of Watts.

Historically, however, energy was not a single category of study; estimates of energy supply instead were disparate, including volumes of wood, weight of coal, and numbers of waterwheels and animals, among other things (Daggett 2019). Census-takers surveyed the installed motive power in industry in the 1870s Census, and did a one-time general survey of fuel wood consumption, but not one of "energy" as a whole (Government Printing Office 1872). Early surveys of fuels were inconsistent in their comprehensiveness and level of detail. New or emerging forms of energy use especially took time to be noticed—as was the case with internal combustion engines, both in transportation and in agriculture. Energy forms that did not pass entirely through the market economy or were consumed at small scales—animal power, fuel wood, and household consumption—sometimes went completely ignored. This presents serious problems for estimates in earlier periods, when these sources comprised the bulk of energy use.

However, we can approximate these numbers through proxy data. In the case of agriculture, this is often straightforward. The number of tractors in operation across the United States was tracked by the Census from virtually the beginning (tractors were commercialized around 1900) as an obviously important piece of farm equipment. Since both this and the amount of gasoline consumed in tractors is known in 1940, if we assume the amount of fuel used per tractor stayed relatively steady across two decades, we can use this to approximate the use of petroleum in agriculture between 1910 and 1930.[5] Similarly, the use of energy in industry, including of food processing, began to be recorded in the 1910 Census; extending it back any further can be done by scaling against variables we do have, likewise recorded by the Census. Of the most energy-intensive processes in the food system in 1910 (liquor distillation, ice manufacturing, meatpacking, flour milling, baking, and sugar refining), each can be scaled using data series extending at least to the middle of the nineteenth century (the quantity of liquor distilled was recorded for tax purposes; ice harvested from lakes and rivers was recorded by distributors; the amount of meat produced nationally was tracked quite early on, etc.). We also occasionally use proxies to infer the direction of overall sectors based on a few subsectors (e.g., industry overall, pre-1900, can be inferred using large and typical sectors: ironworking, brickmaking, glassblowing, and cement manufacture).

The limitations of proxy data mean such estimates must assume the energy input is roughly similar for a given unit of output. While the fuel used in tractors changed little across their first twenty years, variability can be considerable in other places. Industries surely changed over time, even within industries producing roughly similar products in 1800 and 1900. Yet assuming some kind of efficiency increase (due to technological improvements) would render the data useless for drawing any conclusions about the efficiency of the economy—a major goal in our larger work. This is particularly true when the data series in question is both a large portion of the economy and highly variable.

In other words, it is particularly true in the case of something like agriculture. Agriculture was the second largest sector by energy use until the 1860s, and most of its on-field power, before the tractor, came from horses. But unlike these prior examples, we cannot simply use the number of horses as a proxy variable for the energy used in animal feed. This is because horses were and are tremendously variable in feeding requirements, and targeted breeding efforts (and the importation of desirable breeds from abroad) in the nineteenth century specifically pushed the average American horse into a continuous spiral of growth. Horses in 1900 were about 50% larger and stronger than their ancestors in 1800 (McShane and Tarr 2011; R. Woods 2017).

Instead of simply scaling the quantity of feed by the number of horses, then, we also scale it by the size and power of an average horse. The feeding requirements for horses were estimated by various contemporaries for a wide variety of reasons. Gentlemen farmers wanted to chart the costs of their hobby, career farmers, the cost of investing in livestock. The US Army, using horses throughout the period 1800–1920, sought to understand its logistics. We use these feed estimates to produce estimates of horse power across time: the amount of feed consumed is equivalent to the primary energy consumed in powering the agricultural sector. In the next section, we use these to derive an estimate of the total energy used by all horses in U.S. agriculture. These are reproduced here (Table 1).

Estimating the total number of horses is also nontrivial. Before 1840, there were no census records of horses. Here, we turn to prior historians' estimates—based on archival work, they have estimated the total number of draft animals as being roughly one for every three Americans in 1800, a number very close to the proportion in the first national agricultural census in 1840. The same estimates suggest two thirds of these animals were oxen in 1800 (Greene 2008). (Unfortunately, oxen were not tracked in the 1840 census, but appeared in the 1850 census, at which point they were roughly one quarter the total number of working stock.) In order to estimate the total of on-field power before 1840, we thus make three informed assumptions: (1) the ratio of draft animals to humans was 1:3 across the period of 1800 to 1840; (2) in 1800, the ratio of horses to oxen were 1:2, but this number shifted linearly to 3:1 by 1850; (3) the quantity of feed for horses remained relatively constant over this half century, as did that for oxen. We

Table 1. Horse feed estimates, 1810–1922.

Year	Summary of feeding	Lower bound (W)	Upper bound (W)
1810	16–20 quarts of oats/day	1356	1695
1838	25 lb straw plus 3.125 lb oats; alternatively, 14–16 lb corn	1203	1225
1858	30 lb straw		1152
1861	14 lb hay; 12 lb oats		1555
1866	8 parts oats + 2 parts beans + 20 parts hay; totaling 34–36 lb	1831	1939
1892	26 pounds per day, of a mixture that's 16338 pounds grain and 11975 pounds hay across their feeding period	1550	
1892	The most worked horses range from 10 to 14 lb hay; 18 to 20 lb grain	1737	2041
1894	15 lb hay and 9 lb oats	1253	1339
1897	free feeding: 14.4 lb hay, 10.4 lb corn, and 7.55 lb silage for the average animal	1571	
1902	22 lb hay; 15 lb oats		2116
1903	For farm horses at medium work, 10 lb oats, 10 lb hay, 3 lb straw	1198	
1911	16.56 grain and 15.85 hay		1854
1912	15 lb digestible starch for a 1000 lb animal, adjusted to 1400 lb animal		1779
1920	For 1400 lb horse at mod. work, 14–17.5 lb hay, 10.5 to 14 lb grain/day	1327	1725
1922	15.77 to 18.3 lb grain, 14.43 to 18.75 hay per day	1740	2096

These summarize the estimates of various American horse breeders, farmers, and scientists as to the feeding requirements for their working stock. The estimates of food (in the second column) are converted *via* calorie estimates into estimates of energy (joules), then converted into power (watts, columns three and four). There is an overall moderate positive trendline over time. By evaluating how strenuously each set of horses worked and monitoring the overall trendlines of both upper and lower bounds of estimates, we can establish a shifting quantity of feed input over time (Carroll 1920; Edmonds 1922; Gleason 1892; Holt 1861, 1911; Jennings 1866; Knowlson 1810; Langworthy 1903; Merrill 1902; Mills 1894; Nourse 1897; Rarey 1858; Sanborn 1891; Stewart 1838; Woodruff 1912).

use these to produce the earliest part of our draft animal power estimates.

Even adjusting for historical context, not all energy is the same. In agriculture, this is most obviously true in the many engines employed to perform farm work: horses and humans for the first half of American history, and tractors and electric motors in the second half. Human power, notably, comprises a tiny proportion of the overall energy flow (an estimate is provided in Supplementary Figure S.5), never more than ten percent of the total power on farms—humans are far more valuable for their dexterity than for raw power.

But horses, humans, and tractors, at least, are all essentially similar, turning the chemical energy of various fuels into a single output: mechanical work. Electric motors (here mostly used in factory farms) have an additional step—an "upstream" transformation of some form of energy into electricity. Assuming we can find numbers for each of these, with a factory farm's energy use might be enumerated in three very different statistics: energy output (the power of motors, lights, etc.), energy input (the electricity bought by the farm), and the energy input into the power plant (the coal used in a power plant for the electricity bought by the farm). Any of the three would be a reasonable descriptor for the sectoral use of energy.

In agriculture as well as in our larger project, we attempt to prioritize statistics revealing hidden or embodied energy. In the food system, many processes involve heavy inputs of heat: cooking, refining, and so on. This "process heat" is often contrasted with "comfort heat"—the use of heat in homes and businesses to ensure their habitability for humans (and animals). But long-term historical statistics include periods in which "comfort" and "process" heat are usually coming out of the same device at the same time (a cast iron stove or open hearth)! The heat leaking out of a stove is not clearly "wasted" (as it heats the room), but it is also not clearly useful (at what point past mere survival is a stove "wasting" its heat?). Trying to compare different kinds of energy makes it clear there cannot be any single, physics-based economy-wide statistic of "efficiency"—something much sought in the energy intensity literature.

In the end, this leaves us with energy inputs as the most straightforward way to measure energy use comparably across sectors and time. We measure a sector by the "primary energy"—the amount of fuels input, and count the fuels expended in electricity generation for sectors using electricity. Not counting the energy expended in electricity generation would make non-electrified sectors look more significant—but this is simply statistically punishing some for having their combustion engines at the point of use (automobiles) while ignoring the combustion used by others because it is at a power plant. This is especially egregious in historical times, when the difference in efficiency between an electric engine and a combustion engine could be tenfold or more. A similar logic motivates our decisions around renewable energy—does a fuel "input" correspond with the amount of gravitational potential energy carried by the river, with an implied "efficiency" for turning turbines? Some estimates simply assign renewables the same efficiency as fossil fuel generation, giving it a phantom "fuel" input.[6] This has the advantage of allowing easy comparison of renewable and fossil fuel contributions to the electricity grid, but at the cost of having renewable energy vary with an unrelated set of efficiency gains—about 6–8 fold over the course of American history.[7] Ultimately, our goal is to create estimates broadly comparable across time periods and sectors.

These estimates must be somehow bounded. Virtually the entirety of an agroecosystem could be reasonably included in agricultural energy use if not all solar insolation, while the larger energy economy might include large flows of embodied energy or flows affecting human energy production like global wind patterns. Generally, studies of energy use across the U.S. economy have been quite tightly restricted to fuels literally burned or somehow used in electricity generation (Energy Information Administration 2012; IEA 2023; Lawrence Livermore National Laboratories 2019; Schurr and Netschert 1960). By contrast, studies of European countries sometimes include food for animals used in meat production, or unharvested biomass, or others. Our main estimates are limited to on-field power, in large part to facilitate comparability between agriculture and other sectors (our primary goal with the larger dataset). Animal feed might be roughly analogous to materials used in other sectors having similarly large embodied energy from non-human inputs. We do, however, include an estimate of meat-production animal feed in our supplemental documentation—surprisingly, this does not substantially change our larger conclusions about American agriculture. American energy per capita in animal feed has remained remarkably steady.

Results

A human being consumes about as much energy as an incandescent light bulb. At 2000 kilocalories per day, we consume about 100 Watts in food (more or less, depending on the size and activity level of the person). Agricultural energy use in our estimates is the amount of on-field energy required in the production of these food calories; and for American settler societies, this number has historically been high. In the year 1800, this was about 433 Watts per person. In more relatable terms: feeding each human required animal labor equivalent to four or five more humans. Today, that ratio is much closer to one to two (we use about 150 Watts per person in agriculture today). On a per capita basis, American on-field agricultural energy use has only declined over time (Figure 1).

Unsurprisingly, the increase in the American population means the *absolute* quantity of agricultural energy use has significantly increased: roughly twenty times between 1800 and 2020. Yet this figure grew only around 1.27 times between 1900 and 2020: Americans feed 5x the population in 2020 as they did in 1900, with a wider variety of foods, on *roughly the same amount of agricultural land and roughly the same amount of energy.*[8] Indeed, the overall story that agriculture has remained similarly energy intensive holds true even if we add estimates of the embodied energy from inputs of fertilizer and pesticides, taken from other historical estimates (Cao, Lu, and Yu 2018; J. Woods et al. 2010); see Supplementary Figures S.1–S.4.[9]

We argue switching from horse to tractor prompted a decline in per capita on-field power because tractors require little to no energy in maintenance during idle periods. Horses, of course, have significant metabolic requirements. The metabolism of food energy into work operated at similar efficiencies to those of gasoline or diesel engines of tractors, but the cost of maintaining a horse through non-working periods was significant—even though horses burn significantly less energy when idle.[10] In a 1917 USDA survey, they found maize farms required about half the horse labor in winter as they did in summer; on wheat farms, the number was closer to 0% of capacity during winter (Government Printing Office 1918). Tractors could match energy demands far more closely.

What if we add food processing? The above figures do include factory farms, with the bulk of electricity being used in broiler chicken operations (Hitaj and Suttles 2016). But most processing is categorized under industry. Nevertheless, even industrial food systems have decreased on a per capita basis since statistics began to be kept in 1910 (Figure 2). Extrapolating them back in time using proxy data as covered above, we find a slight increase since 1800, but at barely over a hundred watts per capita at its peak, that is hardly enough to erase the relatively low intensity of modern on-field use. Transportation of food is the only area in which this number may have increased—per capita energy use in transportation more broadly has increased four-fold between 1900 and 2020, and more than sixty-fold since 1800. While similar quantities of food are produced per person today and most freight ships something else, foodstuffs are moved far greater distances than in 1800, when most food was grown and consumed in the same place. Unfortunately, statistics in the transportation sector are too inconsistently kept to reach a definitive conclusion.

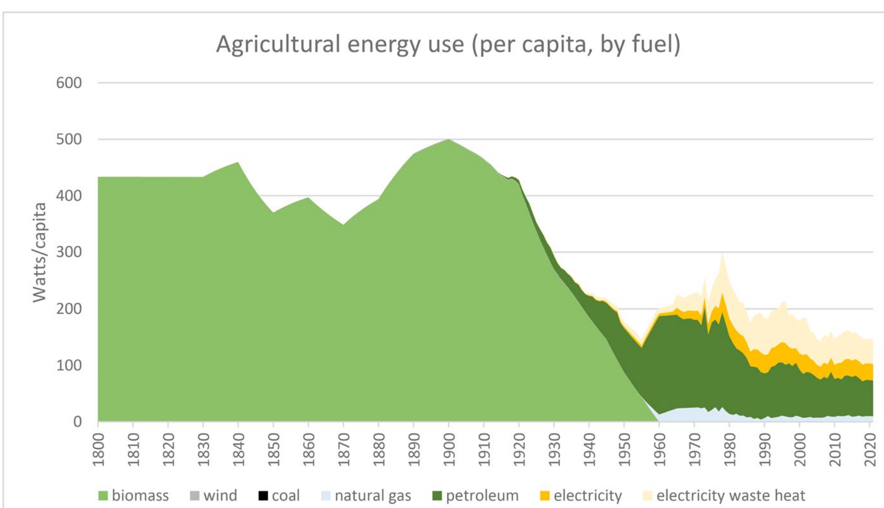

Figure 1. Agricultural energy use (per capita, by fuel), 1800–2019. Reproduction of chart from [STUDY]. This chart shows the overall use of each fuel in on-field agriculture. The adoption of fossil fuels significantly reduced energy expenditures, largely, we argue, because despite similar efficiencies, horses need to be fed when not in use, while tractors do not.

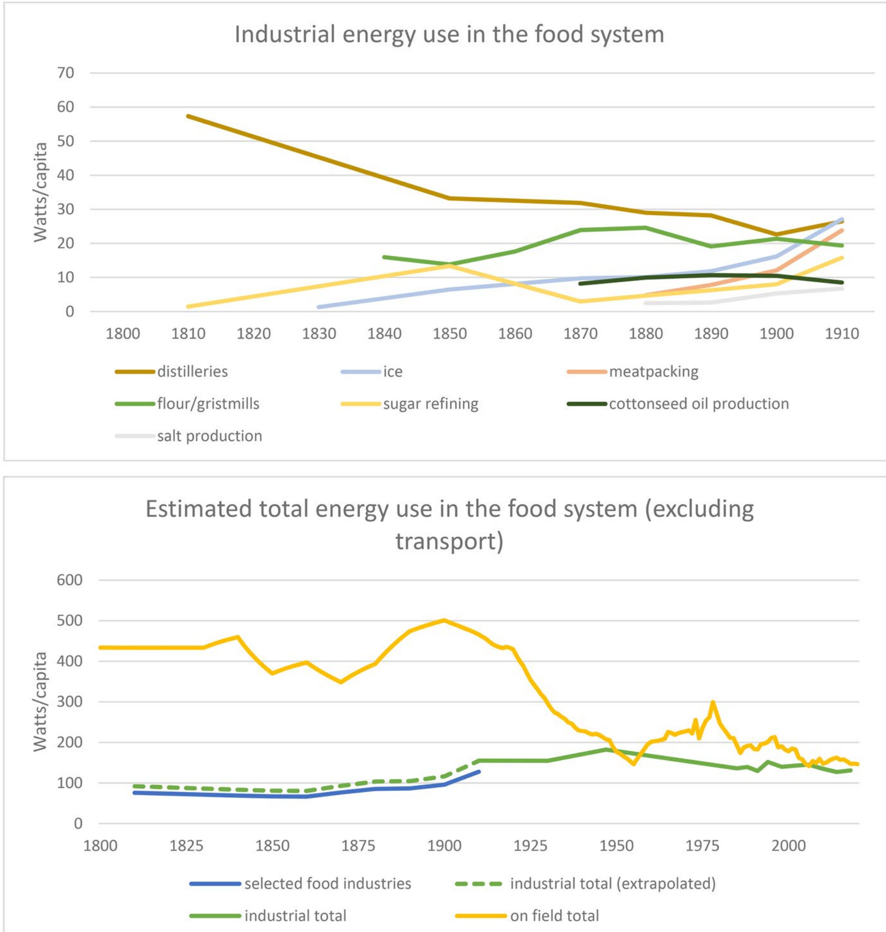

Figure 2. Industrial energy use in the food system, 1800–1910 (top) and estimated total energy use in the food system, 1800–2018 (bottom). These charts show energy consumed per person in the food system (in Watts). The first chart shows estimates of the historical trends of individual industrial processes in the food system. We began with the most energy-expensive processes in 1910 (the first year for which fuel consumption data is available) and extrapolated backwards using proxy data. The second combines these estimates with our on-field estimate to show overall trends in the food system. A modest increase in industrial food energy use does not compensate for the dramatic drop in on-field use. The scaling for each of these sectors will be provided in Supplementary Tables S.2–S.7.

Yet leaving our analysis here would be misleading. For the greatest advantage of the modern food system might lay in cooking. Modern cooking accounts for only 2% of total residential energy use (around 40 Watts per capita) (Energy Information Administration 2022b). The problem with arriving at an earlier estimate is not just that individual residential energy uses were not tracked at the time—it is that they are perhaps untrackable. Before modern radiators emerged in the late nineteenth century, stoves served to both heat the home and cook food (users complained they did neither well). Even earlier, most American homes centered around open hearths at their center (Adams 2014; Cummings 1979; Jenkin 1879). In this context, the distinction between a cooking stove leaking heat away from the food and a home's central heating element performing its task is impossible to draw. Yet we can make a quick estimate. Home cooking elements would surely be in use more than 2% of the time (less than half an hour per day)—and residential energy use in 1800 totaled a staggering 3000 Watts/capita, entirely within these multi-purpose hearths (see Suits, Matteson, and Moyer 2020). Even the most generous reading, in other words, would suggest we use less to cook now.

Conclusion

Absent large scale population decline, improving per capita energy use may play a major role in future climate mitigation efforts. Efforts aimed at improving the "energy intensity" of our economies seek to mitigate climate impacts without seriously undermining living standards. This is the opposite of trends that have occurred in the United States, which has seen a three-fold increase in per capita use. In the particular case of agriculture, however, per capita on field power has seen a slight decrease—the amount of fuel required to feed a single person has gone downwards. This is a remarkable trend, and as detailed in our supplemental documentation, does not seem to be an artifact of how we constructed our dataset.

Industrial agriculture did not represent a radical increase in per capita energy use from the pre-industrial agricultural system—in the United States. Nor does it represent a radical increase or decrease in the quantity of calories Americans consumed per person, nor even the amount of meat they ate. Industrial processes increased the relative quantity of chicken to beef and pork, and the amount of fresh fruit and vegetables, but without any significant increase in per capita energy. Pre-industrial American agriculture was a massive consumer of energy by any measure, roughly on par with industrial agriculture on a per capita basis, as was the pre-industrial household more generally. This appears to be highly unusual to the American case, and it surely merits further study.

One vital caveat, however: that this is not historically bad does not mean it could not be better. The energy savings gained by switching from horses to tractors, and even the ability to increase food production on the same acreage to match a growing population, have mostly been used by Americans to maintain an unusually high level of consumption of meat and dairy over time. Given the relative proportion of electricity and petroleum in agricultural power (with petroleum largely devoted to cropland and electricity to factory-raised stock), had Americans eaten no meat, our per capita use would have declined still further—and the *absolute* energy use would likewise have declined over the course of the twentieth century, even with a growing population. Moreover, this point—that an energy-intensive agricultural sector is not novel—does not mean American agriculture is sustainable. The unsustainability of modern American agriculture lies not in energy, but in its numerous other biological impacts: land use change, biodiversity loss, interruption of biogeochemical flows, freshwater use, erosion, and so on (Rockström 2009). If anything, this data highlights the multiplicity and complexity of the present-day crisis.

Notes

1. Definitions can be found in Grubler (2014, 1–118). Note the unconventional application of "primary energy" in our paper; we track the total primary energy both consumed in a sector and in upstream transformations—e.g. we attribute to a feedlot the electricity it consumes, as well as the fuel *required to generate that electricity.* If one only tracks final energy, then a sector might appear to "use less energy" and "have lower carbon emissions" by switching from internal combustion motors to electric motors, even if those electric motors were run on coal power.
2. Of the works cited above on U.S. history, only De Stercke, *Dynamics of Energy Systems,* attempts to disaggregate by economic sector, and splits the economy into "residential," "commercial," "industrial," and "transportation." The above roundtable had a regional rather than national study of U.S. agriculture (Cunfer et al. 2018).
3. Some social metabolism of agriculture research that uses per capita units include Soto et al. (2016) and Kuskova, Gingrich, and Krausmann (2008).
4. The Agricultural Census ran concurrently with the Decennial Census before desyncing after 1950.
5. This of course likely somewhat understates the amount of fuel used early on, as tractors likely gained in efficiency over time—but it also overstates it by some amount, as tractors grew larger over time.
6. This is in fact the method used in the Energy Information Administration, "Monthly Energy Review.".
7. For more on power plants and efficiency, see Suits, Matteson, and Moyer (2020, 19).
8. Total crop acreage in 1900 was recorded as roughly 415 million "improved" acres and 841 million total; see *Twelfth Census of the United States, Vol. 5: Agriculture,* p. xviii. The equivalent statistics today are: total crop acreage today, around 392 million acres for crops, and an additional 800 million for grazing (Bigelow and Borchers 2017).
9. A longer estimate of pesticides and fertilizers is included in the supplemental documentation.
10. On the efficiency of muscle power, see Woledge et al. (1985), who give a figure of 25–35%.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Adams, S. P. 2014. *Home fires: How Americans kept warm in the nineteenth century* Baltimore, MD: Johns Hopkins University Press.

Barak, O. 2020. *Powering empire: How coal made the Middle East and sparked global carbonization*. Oakland: University of California Press.

Beltran, A. 2018. Introduction: Energy in history, the history of energy. *Journal of Energy History/Revue D'Histoire de L'Énergie no. 1*. https://energyhistory.eu/en/node/84.

Bigelow, D. P., and A. Borchers. 2017. Major uses of land in the United States. U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=84879

Braudel, F. 1981. *Civilization and capitalism, 15th-18th centuries, vol. 1: The structures of everyday life*, trans. Sian Reynolds, 336–72. London: William Collins Sons & Co. (Orig. 1979)
Cao, P., C. Lu, and Z. Yu. 2018. Historical nitrogen fertilizer use in agricultural ecosystems of the contiguous United States during 1850–2015: Application rate, timing, and fertilizer types. *Earth System Science Data* 10 (2):969–84. doi: 10.5194/essd-10-969-2018.
Carroll, W. 1920. *Feeding work horses*. Logan, UT: Utah Agricultural Experiment Station.
Chatterjee, E. 2020. The Asian anthropocene: Electricity and fossil developmentalism. *The Journal of Asian Studies* 79 (1):3–24. doi: 10.1017/S0021911819000573.
Cipolla, C. M. 1961. Sources d'énergie et histoire de l'humanité. *Annales. Économies, Sociétés, Civilisations* 3:521–534.
Cummings, A. L. 1979. *The framed houses of Massachusetts Bay, 1625-1725*. Cambridge, MA: Belknap Press.
Cunfer, G., A. Watson, and J. MacFadyen. 2018. Profiles of an agricultural frontier: The American great plains, 1850-2000. *Regional Environmental Change* 18 (4):1021–32. doi: 10.1007/s10113-017-1157-x.
Daggett, C. N. 2019. *The birth of energy: Fossil fuels, thermodynamics, and the politics of work*. Durham, NC: Duke University Press.
De Stercke, S. 2017. Dynamics of energy systems: A useful perspective. IIASA interim report. Laxenburg, Austria.
Demuth, B. 2019. *Floating coast: An environmental history of the Bering Strait*. New York: W. W. Norton.
Eaglin, J. 2022. *Sweet fuel: A political and environmental history of Brazilian ethanol*. Oxford: Oxford University Press.
Edmonds, J. 1922. *Feeding farm work horses and mules*. Champaign, IL: University of Illinois Agricultural Experiment Station.
Energy Information Administration. 2012. *Annual energy review 2011*. Washington, DC: U.S. Department of Energy.
Energy Information Administration. 2022a. Monthly energy review. Energy Information Administration. https://www.eia.gov/totalenergy/data/monthly/.
Energy Information Administration. 2022b. Residential energy consumption survey. Energy Information Administration. https://www.eia.gov/consumption/residential/
Etemad, B., and J. Luciani. 1991. *World energy production, 1800-1985: Production mondiale d'énergie, 1800-1985*. Genève: Librairie Droz.
Fouquet, R. 2010. The slow search for solutions: Lessons from historical energy transitions by sector and service. *Energy Policy* 38 (11):6586–96. doi: 10.1016/j.enpol.2010.06.029.
Fouquet, H. 2008. *Power and light: Revolution in energy services*. London: Edward Elgar,
Fouquet, R., and P. J. G. Pearson. 1998. A thousand years of energy use in the United Kingdom. *The Energy Journal* 19 (4):1–41. doi: 10.5547/ISSN0195-6574-EJ-Vol19-No4-1.
Gales, B., A. Kander, P. Malanima, and M. Rubio. 2007. North versus south: Energy transition and energy intensity in Europe over 200 years. *European Review of Economic History* 11 (2):219–53. doi: 10.1017/S1361491607001967.
Gingrich, S., G. Cunfer, and E. Aguilera. 2018. Agroecosystem energy transitions: Exploring the energy-land nexus in the course of industrialization. *Regional Environmental Change* 18 (4):929–36. doi: 10.1007/s10113-018-1322-x.
Gleason, O. 1892. *Gleason's horse book and veterinary adviser: Comprising history, breeding, training, breaking, buying, feeding, grooming, shoeing, doctoring, telling age, and general care of the horse*. Chicago, IL: M.A. Donohue and Co.
Government Printing Office. 1872. *Ninth census of the United States, Vol. 3: The statistics of the wealth and industry of the United States*. Washington, DC: Government Printing Office.
Government Printing Office. 1918. *Yearbook of the United States Department of Agriculture, 1917*. Washington, DC: Government Printing Office.
Greene, A. N. 2008. *Horses at work: Harnessing power in industrial America*. Cambridge, MA: Harvard University Press.
Grubler, A., T. B. Johansson, L. Mundaca, N. Nakicenovic, S. Pachauri, K. Riahi, H.-H. Rogner, K. R. Smith. 2014. *Energy primer*. Laxenburg, Austria: International Institute for Applied Systems Analysis.
Hitaj, C., and S. Suttles. 2016. Trends in U.S. agriculture's consumption and production of energy: Renewable power, shale energy, and cellulosic biomass. *Economic Information Bulletin* 8:1–46.
Holt, J. 1861. *Feeding disabled horses. Letter from the Secretary of War, in answer to a resolution of the House of December 2, 1861, relative to feeding disabled horses during the winter*. Washington, DC: Government Printing Office
Holt, J. 1911. *Feeding farm work horses*. Champaign, IL: University of Illinois Agricultural Experiment Station.
IEA. 2023. *World energy outlook 2023*. Paris IEA. https://www.iea.org/reports/world-energy-outlook-2023.
Jenkin, F. 1879. *Healthy houses*. New York: Harper & Brothers.
Jennings, R. 1866. *The horse and other live stock*. Abingdon: J.E. Potter and Co.
Kander, A., P. Malanima, and P. Warde. 2013. *Power to the people: Energy in Europe over the last five centuries*. Princeton: Princeton UP.
Knowlson, J. 1810. *Complete farrier, or, gentleman's travelling companion*. New York: Bradford and Inskeep.
Krausmann, F., and H. Haberl. 2002. The process of industrialization from the perspective of energetic metabolism socioeconomic energy flows in Austria 1830–1995. *Ecological Economics* 41 (2):177–201. doi: 10.1016/S0921-8009(02)00032-0.
Kuskova, P., S. Gingrich, and F. Krausmann. 2008. Long term changes in social metabolism and land use in Czechoslovakia, 1830–2000: An energy transition under changing political regimes. *Ecological Economics* 68 (1–2):394–407. doi: 10.1016/j.ecolecon.2008.04.006.
Langworthy, C. 1903. *Principles of horse feeding*. Washington, DC: U.S. Dept. of Agriculture.
Lawrence Livermore National Laboratories. 2019. Energy flow charts: Charting the complex relationships among energy, water, and carbon. Accessed September 10, 2020. https://flowcharts.llnl.gov/
Massard-Guilbaud, G. 2018. From the history of sources and sectors to the history of systems and transitions: How the history of energy has been written in France

and beyond. *Journal of Energy History/Revue D'Histoire de L'Énergie no. 1*. https://energyhistory.eu/en/node/88.
McShane, C., and J. Tarr. 2011. *The Horse in the City: Living Machines in the Nineteenth Century*, Baltimore, MD: Johns Hopkins University Press.
Merrill, L. 1902. *Horse feeding*. Logan, UT: Utah Agricultural College Experiment Station.
Mills, A. 1894. *Relative value of corn and oats for horses*. Logan, UT: Utah Agricultural College Experiment Station.
Mitchell, B. R. 2007. *International historical statistics: 1750-2005*. Basingstoke: Palgrave Macmillan.
Montaño, D. J. 2021. *Electrifying Mexico: Technology and the transformation of a modern city*. Austin: University of Texas Press.
National Agricultural Statistical Service Homepage. 2022. United States Department Of Agriculture. https://www.nass.usda.gov/.
Nourse, D. 1897. *Silage for horses*. Blacksburg, VA: Virginia Agricultural Experiment Station.
O'Connor, P., and C. Cleveland. 2014. U.S. energy transitions 1780-2010. *Energies* 7 (12):7955–93. doi: 10.3390/en7127955.
Pallua, I. 2018. A hitchhiker's guide to quantitative energy studies. *Journal of Energy History/Revue D'Histoire de L'Énergie no. 1*. https://energyhistory.eu/en/node/54.
Rarey, J. 1858. *Taming or breaking the horse: By a new and improved method, as practiced with great success in the United States, and in all the countries of Europe*. New York: Dick and Fitzgerald.
Ritchie, H. 11/6/ 2019. Food production is responsible for one-quarter of the world's greenhouse gas emissions. *Our World in Data* https://ourworldindata.org/food-ghg-emissions.
Robert Ayres, L., Ayres Benjamin, and W. Ayres. 2003. Exergy, power and work in the US economy, 1900-1998. *Energy* 28 (3):219–73. doi: 10.1016/S0360-5442(02)00089-0.
Rockström, J., W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, et al. 2009. A safe operating space for humanity. *Nature* 461 (7263):472–5. doi: 10.1038/461472a.
Sanborn, J. 1891. *Feeding hay and grain mixed to horses and feeding cut feed vs. whole hay to horses*. Logan, UT: Utah Agricultural College 1690 Experiment Station.
Schurr, B., and S. Netschert, eds. 1960b. *Energy in the American economy, 1850 - 1975: Its history and prospects*. Milton Lipton.
Schurr, S., and B. Netschert. 1960a. *Energy in the American economy, 1850-1975: An economic study of its history and prospects*. Baltimore, MD: Johns Hopkins University Press,
Seow, V. 2022. *Carbon technocracy: Energy regimes in modern East Asia*, Cambridge, MA: Harvard University Press
Sieferle, R. P. 2001. *The Subterranean Forest: Energy Systems and the Industrial Revolution*, trans. Michael P. Osman. Cambridge: White Horse Press.
Soto, D., J. Infante-Amate, G. I. Guzmán, A. Cid, E. Aguilera, R. García, and M. G. de Molina. 2016. The social metabolism of biomass in Spain, 1900–2008: From food to feed-oriented changes in the agro-ecosystems. *Ecological Economics* 128:130–8. doi: 10.1016/j.ecolecon.2016.04.017.
Stewart, J. 1838. *Stable economy: A treatise on the management of horses in relation to stabling, grooming, feeding, watering, and working*. Edinburgh: W. Blackwood and Sons.
Suits, R., Matteson, N., and Moyer, E. 2020. Energy transitions in U.S. history, 1800-2019: Supplementary information. https://static1.squarespace.com/static/54dcfad0e4b0eaff5e0068bf/t/5fbeba6ffa04221c71019ccc/1606335091993/Suits_Matteson_Moyer_2020_Energy_Transitions.pdf
Unger, R., and J. Thistle. 2013. *Energy consumption in Canada during the 19th and 20th centuries: A statistical outline*. Napoli: Consiglio Nazionale delle Ricerche, Istituto di Studi sulle Società del Mediterraneo.
Woledge, R. C., N. A. Curtin, and E. Homsher. 1985. *Energetic aspects of muscle contraction*. London: Academic Press.
Woodruff, H. 1912. *The economics of feeding horses*. Paris: Baillière, Tindall and Cox.
Woods, R. 2017. *The herds shot round the world: Native breeds and the British Empire, 1800-1900*. Chapel Hill, NC: University of North Carolina Press.
Woods, J., A. Williams, J. K. Hughes, M. Black, and R. Murphy. 2010. Energy and the food system. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 365 (1554):2991–3006. doi: 10.1098/rstb.2010.0172.