

Columbia Studies in the Classical Tradition

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VOLUME 39

The titles published in this series are listed at brill.com/csct

The Ancient Mediterranean Environment between Science and History

Edited by

W.V. Harris



BRILL

LEIDEN · BOSTON
2013

ENERGY CONSUMPTION IN THE ROMAN WORLD*

Paolo Malanima

Economic development has been supported, over the last two centuries, by a technical revolution in the use of power and energy. The introduction of *modern machines*, able to deliver huge quantities of work per unit of time on the one hand, and the availability of cheap *fossil energy sources* on the other, have enormously increased productive capacity. Both changes were the *necessary* although not *sufficient* conditions for the notable discontinuity in the economic history of the human populations and were the main determinants of a huge increase of output. The scarce availability both of mechanical power and energy set a limit to the growth potential of previous agricultural economies from the 5th millennium BC until the start of modern growth two centuries ago, and was the direct determinant of phases of decline or collapse. We cannot but agree with the view presented by E.A. Wrigley on pre-modern agricultural or 'organic' societies. His opinion is that 'societies before the Industrial Revolution were dependent on the annual cycle of plant photosynthesis for both heat and mechanical energy. The quantity of energy available each year was therefore limited, and economic growth was necessarily constrained'.¹ This was the main reason why decreasing returns to labour prevailed in past agricultural civilisations, as the English classical economists maintained.

The topic of energy consumption as a whole has been only marginally investigated in the case of the Roman world (though there has been some attention to particular energy sources such as wood). Previous attempts to quantify energy consumption do not allow one to understand the procedures followed.² It is obviously impossible to present definite figures of energy consumption, since local conditions and the relations between human beings and the environment differed so much within the Roman

* I thank Elio Lo Cascio for his comments on a previous draft of this paper. I also thank the participants in the conference 'Growth and Factors of Growth in the Ancient Economy', January 28–29, 2011, held in Chicago (with the support of the Federal Reserve Bank of Chicago), and particularly Alain Bresson and Joel Mokyr, for their comments.

¹ Wrigley 2013, 1. See also Wrigley 2010 on the same topic.

² See the Appendix.

Empire. It is possible, however, to present plausible data and plausible confidence intervals around the figures. This is a first step towards a comparison of energy consumption within past societies and between past societies and the present world.

The purpose of the present work is to focus on energy consumption in the early Roman Empire; and, in particular, to identify the energy sources (§ 1), to quantify their exploitation (§ 2–3), and their constraints to the growth potential (§ 4–5). The last section (§ 6) will be devoted to the dynamics of the ancient energy systems, that is the innovations in the technical exploitation of energy and its availability. The Appendix will present the procedure followed in the quantification of energy consumption in the Roman Empire and discuss alternative estimates.

L. THE INPUT OF ENERGY

Often it is not completely clear what actually were the sources of energy in past agrarian civilizations.³ The consequence is that any quantification becomes imprecise or, indeed, quite impossible. Although certainty is unattainable on the subject, a plausible order of magnitude is not out of reach.⁴

There were three main inputs of energy in pre-modern agrarian civilizations from about 5000 BC until 1800 AD: *food*, *firewood* and *fodder for working animals*.⁵

Food has been the primary source of energy since the beginning of the human species. A second source, *firewood*, began to be exploited as fuel between 1,000,000 and 500,000 years ago. From then until the Industrial Revolution it was the main provider of heat.⁶ The third source, *fodder for draft animals*, began to supply mechanical work in the agricultural civilizations between 5000 and 4000 BC, that is since the exploitation of animal power on a wide scale in agriculture and transportation. These were still the main

³ Here I refer to the energy sources with a cost (often an opportunity cost). Solar light is important for our survival, but is free and then excluded from our calculations. The same holds true for the vegetation of a forest, when not exploited by the humans. Water and wind power, when exploited through mills and sails (expensive to build), is included, while it is excluded when not exploited for some productive activity. See, however, the Appendix for more information on the subject.

⁴ I have discussed this topic in greater depth in Malanima (forthcoming). See the following Appendix on the quantification of energy consumption in the early Roman Empire.

⁵ I have examined the transitions among energy systems in greater depth in Malanima 2010.

⁶ Perès 1977; Goudsblom 1992.

energy carriers of ancient Mediterranean civilization. The discovery of fire on the one hand and the exploitation of draft animals on the other, marked two main changes in the history of technology. The most recent change has been the spread of thermal machines over the last two centuries. In the long period between the first exploitation of animal power in agriculture and the steam engine, so for almost seven millennia, no radical change, or macroinvention,⁷ occurred in the exploitation of energy, although several minor changes took place.

Food consumption has not changed so very much during the long history of mankind, at least in term of calories. Even in the case of ancient Greek and Roman civilizations, we can assume a daily average consumption of 2–3,000 calories⁸ as recent estimates indicate. In particular, 'the diet of the Mediterranean region with its high population density was probably marked by much lower overall meat consumption'.⁹ Pork meat 'was a prominent food of the urban high-income strata of society, whereas the poorer ancient Roman population consumed primarily vegetarian food'.¹⁰ Although within a wide geographic area such as the Roman Empire differences in diet were remarkable, the intake of calories was necessarily similar.¹¹

Regional variations in firewood consumption were much wider and depended on two main variables: temperature and industrial demand. In Mediterranean civilizations the amount of 1 kg. of wood (that is about 3,000 kcal.) per head per day can be assumed as the lower margin of a likely range, given the relatively high temperature in this area of the world. Calculations of industrial consumption by metallurgy and other industries (such as pottery, glass and tile production) and services (such as baths) suggest that another half kg. could be added to this daily amount, at least in regions with widespread industrial activity. This half kg. more is, however, a relatively high estimate, based on what we know on early Modern Europe.¹² For the early Roman Empire only rough estimates on wood consumption by metallurgy are possible.¹³ Differences in firewood consumption certainly existed within the Roman world and derived from the regional differences

⁷ I use here the word 'macroinvention' following Mokyr 1990.

⁸ Here I use the terms of kilocalorie (kcal.) or calorie as synonyms, although they are not. Actually, a kilocalorie (the correct unit of measure when we speak of food or heat) is 1,000 calories.

⁹ Koepke and Baten 2008, 132.

¹⁰ Koepke and Baten 2008, 142.

¹¹ See Jongman 2007b.

¹² Kander et al. 2013.

¹³ See the Appendix.

in temperature and industrial development. A range between 1 and 2 kg., that is between 3,000 and 6,000 calories per head per day, seems plausible.¹⁴ According to a calculation of biofuels consumption on a world scale about 1850, that is when wood was still the main fuel, the per capita average was 2.3 kg. and this average was far lower in the South.¹⁵ When taking into account the high temperatures in the Southern Mediterranean and the existence of regions with poor industrial activity, a lower estimate of firewood consumption of about 3,000 kcal. per head per day, that is 1 kg., seems plausible for the Roman Empire. A consumption of 6,000 kcal, equivalent to 2 kg. of wood, could however have been reached in cold regions, in the mountains, or in areas with relatively high industrial activity.¹⁶

As to the contribution by draft animals to the energy balance, an estimate can be based on the ratio between their consumption of fodder (expressed in some energy measure) and population. We follow, in this case, the same procedure we use today to establish the average consumption of oil in a country: that is, dividing the oil consumed among the population. The only difference being that in pre-modern agrarian civilizations, we are mainly dealing with biological converters and that their fuel is food intake. From the available information on the size of ancient working animals¹⁷ and the draft animals-population ratio,¹⁸ we then estimate how much energy was consumed per head dividing the calories of fodder intake by the population. The range of a plausible consumption is 1,000–2,000 kcal. per head per day.

The only energy carriers not provided by the land through photosynthesis in ancient agricultural civilizations were wind, used to drive sailing ships, and water, exploited for mills as from the 3rd century BC.¹⁹ An estimate of the consumption of the energy of wind and water is difficult.²⁰ We know, however, for the early Modern Age, that their contribution to the energy balance hardly represented more than 1 percent of the total energy consumed. It seems plausible to assume that watermills and sailing ships were not more numerous in the Roman Empire than in medieval and early modern Europe.

¹⁴ The article by Harris 2004 is important for the quantification of firewood consumption.

¹⁵ Fernandes et al. 2007 (see the auxiliary material for the article in <http://onlinelibrary.wiley.com/doi/10.1029/2006G002895/supplinfo>). The consumption of biofuels in the Mediterranean regions was lower than the average.

¹⁶ See the lower energy consumption proposed by Smil 2000, reported in the Appendix to this paper.

¹⁷ On the topic see in particular Krom 2000, 2002, and 2004. See also Ward-Perkins 2005, Ch. VII and Fig. 7.3.

¹⁸ This ratio is hard to establish for ancient economies. See, however, the Appendix.

¹⁹ Wilson 2002a and 2008b and Lo Cascio and Malanima 2008.

²⁰ But see the Appendix.

In mere quantitative terms, the role of wind and water in pre-modern agrarian societies was negligible, although they were very important from the technological viewpoint. Actually, sailing ships and watermills were the only engines whose mechanical work did not derive from the metabolism of food.²¹ Together these engines provided 100 percent of the mechanical energy by non-biological converters.

2. A QUANTIFICATION

Table 1 presents a likely consumption range for the ancient Mediterranean in the age of the early Roman Empire, that is the 1st century and the first half of the 2nd, up until the Antonine Plague. As we see, energy consumption is comprised between 6,000 and 11,000 kcal. per capita per day (or 9.2–18.4 Gigajoules per year). We see also that half of consumption consisted of food for humans and draft animals, the other half of firewood.

Table 1. Energy consumption in the early Roman Empire (in GJ. per capita per year and kcal. per capita per day).

Sources of energy	Gj/year		Kcal/day		%	
	Min.	Max.	Min.	Max.	Min.	Max.
Food for humans	3.1	4.6	2,000	3,000	33	27
Fuel	4.6	9.2	3,000	6,000	50	55
Fodder for animals	1.5	3.0	1,000	2,000	17	18
<i>Total</i>	9.2	16.8	6,000	11,000	100	100

Sources: see text and Appendix.

Today World energy consumption is 50,000 kcal. per capita per day or 76.5 gigajoules (Gj.) per year. In Europe it is notably higher: 100,000 kcal. per day (153 Gj. per year). At the beginning of modern growth, in the early decades of the 19th century, World average consumption per capita was 7–10,000 kcal. per day (10–15 Gj. per year) and the European 15,000 kcal. per day (23 Gj. per year).²² Around 1850, consumption per head of the three main sources of energy (food, firewood and fodder) in Northern Mediterranean

²¹ Technical change in maritime technology was continuous and certainly contributed to enhance the exploitation of wind power, although, in mere quantitative terms, the energy consumed by sailing ships remained modest. See now, on changes in maritime technology, Harris and Lara 2011.

²² Malanima 1996 and 2010.

countries (Portugal, Spain, France, Italy) ranged between 11,500 and 13,500 kcal. per day.²³ A Mediterranean average including Northern Africa and the Near East (for which we have no data until 1970) would certainly be lower.²⁴ Thus, a plausible result is that per capita energy consumption in the ancient Roman world was 5–6 times less than the World average in 2000 and 10 times less than the European average at the same date. It was also a little lower than that of the Northern Mediterranean countries at the beginning of industrialisation. The Roman Empire included many Southern regions, where the consumption of firewood was certainly lower than in the Mediterranean countries of Europe at the start of industrialisation.

It is hard to specify the impact of the production of energy on the environment in the early Roman Empire. If we assume that food production required half a hectare per capita,²⁵ firewood half a hectare of forest and fodder for draft animals another half hectare, then per capita requirement was 1.5 hectares. This estimate is nothing but a plausible average (based mainly on late medieval-early modern European examples, where the productivity of fields, meadows and forests was quite similar to that in Roman antiquity).

In around 165 AD, the Roman Empire measured 3,800,000 km².²⁶ Accepting the previous calculations regarding consumption and soil per head, to provide energy for the 70 million inhabitants living in the Empire 1,050,000 km² were necessary, which is 25–30 percent of the total. If we assume a population of 100 million, plausible as well for the middle of the 2nd century AD, the need of soil to support energy production becomes 1,500,000 km², which is 40 percent of the Empire. If we exclude the mountains (lands more than 600 metres high), which in the Mediterranean regions cover 20–25 percent of the total area and were hard to exploit, the extent of the agrarian soil in the Roman Empire becomes about 3,000,000 km². In this case, according to the two previous population estimates, the share covered by fields, exploitable woods and meadows becomes respectively 33 and 50 percent of the total area. These shares naturally rise if we subtract from the total extent not only the mountains, but also hilly lands hard to cultivate, marshes, lakes and urban areas.

²³ Kander et al. 2013.

²⁴ For these countries the series elaborated by IEA (International Energy Agency) start only from the 1970s.

²⁵ Fallow land is not included.

²⁶ I take both the extent of the Empire and the inhabitants from Scheidel 2017, 48.

3. EFFICIENCY AND ENERGY INTENSITY

Only a part of energy input is actually transformed into useful energy (or energy services, that is mechanical work, light and useful heat). How great this share is depends on the efficiency of the converters of energy, that is labour (*L*) and capital goods (*K*). The thermodynamic efficiency (η) of the system of energy can be represented through the following ratio between the energy services (*E_u*) and the total input of energy (*E_I*):

$$\eta = \frac{E_u}{E_I}$$

Today, in our developed economies, this ratio is about 0.35; that is 35 percent of the input of energy becomes actual mechanical work, light or useful heat. In past agricultural civilizations, the efficiency was much lower. A plausible calculation is easier for the past, when biological converters prevailed, than for the present. Today, in fact, the variety of machines, with diverse yields, make any estimate hard. The ratio between useful mechanical work and input of energy into biological converters, such as humans and working animals, is around 15–20 percent.²⁷ Part of the intake of energy in the form of food is not digested and is expelled as waste, whilst the main part is utilized as metabolic energy in order to repair the cells, digest and preserve body heat. A human being or animal consumes even when inactive. The use of firewood is even less efficient. The greater part of the heat is dispersed without any benefit for those who burn the wood. Its yield is about 5–10 percent. Overall, the efficiency of a vegetable energy system based on biological converters, such as that of ancient civilizations, was around 15 per cent at the most: that is 1,000–1,500 kcal. were transformed into useful mechanical work or heat; the rest was lost. Thermal machines are much more efficient than biological converters such as animals and humans.

Another measure of efficiency in the use of energy is the ratio between the energy input and output, that is GDP. It represents the energy intensity, or the quantity of energy we need to produce a unit of output (*Y*):

$$i = \frac{E_I}{Y}$$

²⁷ See the useful Herman 2007.

This ratio depends on the efficiency of the converters, but, contrary to the previous ratio, it also depends on the structure of production, that is the relative importance of the different sectors and subsectors within the economy. Some sectors (e.g. industry and especially heavy industry) consume much more energy per unit of output than others (e.g. some services). If there is a change in the relative importance of any specific sector, energy intensity changes as well, even without any change in the thermodynamic efficiency of the converters. It is apparent that the impact of energy use on the environment depends both on the amount of energy exploitation and on energy intensity; higher intensity implying a higher impact on the environment. In past agricultural civilizations, for any unit of GDP (e.g. 1 dollar), the expense of energy was higher than today. Around 2000, in Western Europe, energy intensity was 7–8 Megajoules per dollar.²⁸ In past agrarian economies it was at least twice as much, since mechanical converters of energy are more efficient than biological converters. In 1800 Western Europe, that is before the start of industrialization, it was 12–14 Megajoules per dollar. Assuming that in the early Roman Empire energy intensity was the same as in pre-modern European societies, the level of per capita GDP would be about 1,000 dollars (1990 Intern. \$ Purchasing Parity Power).²⁹

4. THE ENERGY CONSTRAINTS

Vegetable energy carriers, such as those exploited in past pre-modern civilizations, are reproducible. The sun's energy enables a continuous flow of exploitable phytomass and the circulation of water and wind. Although the availability of these carriers was and is endless,³⁰ and the energy system based on them was and is sustainable, their increase was hard and time-consuming. A large part of working time in pre-modern economies was aimed at providing energy. All in all, the expense³¹ for energy (food, firewood and fodder) could represent 60–70 percent of the average income. In pre-modern economies consumption represented, at least, 80 percent of GDP.³²

²⁸ International 1990 Geary-Khamis dollars Purchasing Parity Power.

²⁹ See on the topic Lo Cascio and Malanima 2009; forthcoming.

³⁰ Actually, it is not endless, but the Sun's light will still reach the Earth for 5 billion years.

³¹ Including the opportunity cost when a source of energy is provided directly by the consumer himself.

³² Malanima 2009, chap. VII.

Although this 80 percent was not devoted completely to providing energy, the expense for food and firewood was remarkable.

Since all sources of energy came from the soil and soil is not endless, the consequence during epochs of demographic rise was a fall in soil per worker and then decreasing returns to labour. The main change taking place from the start of modern growth has been the elimination of the dependence of the energy system on the soil's constraint. When demand increases, it is much easier to provide coal, oil or natural gas, than the vegetable carriers utilized in past agrarian economies. Since in pre-modern organic vegetable energy systems, the transformation of the Sun's radiation by plants into phytomass, thanks to photosynthesis, was central and climatic conditions can heavily influence the output of energy, climatic phases marked the past history of mankind. Short-term deviations from the average temperature or precipitations resulted in dramatic increases or falls in energy availability: the well-known years of plenty and the frequent famines of the agricultural economies. Long-run changes were much less felt or were even unnoticed, although they influenced agricultural production, thus the overall availability of energy, and, consequently, total output and population trends.

The second important constraint of all pre-modern energy systems was the low power of the converters, which resulted in a low working capacity per unit of time. The high standard of living of modern societies is the result of the higher output per unit of time or higher labour productivity. The power of a man in everyday work is the same as a 40-watt lamp, or 0.05–0.07 Horse Power (HP). The power of a horse is 15–20 times higher. In pre-modern civilizations, the most powerful engines were watermills, whose power was about 3 HP, and sailing ships, which could even reach 50 HP.³³ To clarify this central point about the differences between past and modern energy systems, we must remember that the power of an average car (80 kilowatts) is equal to the power of 2,000 people and that the power of a big generating electric station (800 megawatts) is the same as that of 20 million people. The electric power of a medium sized nation such as Italy in 2000 equals 80,000 megawatts, which is the same power as that of 2 billion people. Today, a nuclear plant or a nuclear bomb can concentrate millions of HP, or the work of many generations of humans and draft animals, into a small space and a fraction of time.

³³ I neglect here the employment of power for military purposes. A catapult was an ingenious concentration of power.

While the adoption of new energy carriers in the past two centuries has greatly expanded the *quantity* of energy at our disposal, an equally key development has been new technology (machinery) able to concentrate large amounts of work in particular locations in order to carry out specific tasks. This *concentration of work* allows humans to accomplish tasks that were barely imaginable just a few lifetimes ago. It was the first step toward a new control of the natural forces at a level inconceivable in past agrarian civilizations.

5. INNOVATIONS

The progress of technology in the ancient Mediterranean world did not reveal interruptions or declines:³⁴ the use of machines was more widespread in ancient Greece and Rome, together with ancient China, than in any other civilization until certainly the 12th or perhaps the 14th century A.D. in Western Europe.³⁵ On the other hand, looking at the problem of technical innovation from the viewpoint of energy, Roman technology consisted primarily, as J-P. Vernant wrote, 'in the application of the human and animal force through a variety of tools, and not in the utilisation of the forces of nature through the use of machines.'³⁶ The introduction of new tools, that is micro-inventions, was continuous. In a sense this flow of innovations made human work more efficient, although this increase in efficiency, from the specific viewpoint of energy and power, was modest indeed.

As suggested by A. Bresson, in the 1st century AD,³⁷ Hero's work demonstrates the knowledge of all the main elements for constructing a steam engine, such as the conversion from rotatory to alternating movement, the cylinder and piston, non-return valves and gears: 'the main technical elements embodied in the Newcomen engine were, if not in function at least well known in the Hellenistic age'.³⁸ We can wonder, however, how widespread this knowledge actually was. With the exception of Hero's work, no other mention of the use of steam is available in ancient literary texts or archaeological remains.

We know that in England coal began to be used on a wide scale from the 1st century AD both for domestic usage and for the melting of metals.

³⁴ Greene 2000; Schneider 2007.

³⁵ Wilson 2008b, 362.

³⁶ Vernant 1957, 207.

³⁷ Described in *Pneumatica* 2.11.

³⁸ Bresson 2006, 72.

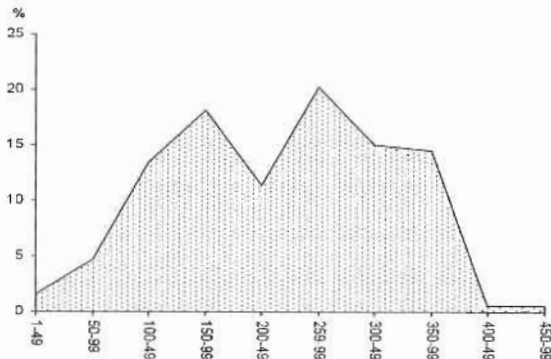


Fig. 1. Dated remains of coal in England 1–500 AD (% of the total dated remains every 50 years). Source: based on data in Smith 1997.

Coal has been recovered from 70 archaeological sites in England and Wales. Its chemical analysis has allowed these remains to be dated (Figure 1).³⁹ Although we cannot quantify the level of consumption, we can specify the chronology of its exploitation. When the Romans conquered England, coal was already exploited. Its utilization spread and attained a maximum level from the 2nd until the 4th century. At least until the 5th century AD, coal continued to be used on a wide scale. Later it almost disappeared.

Coal, however, is very unevenly distributed across the globe, and, apart from Australia, is almost entirely found in a few parts of the Northern hemisphere, that is, North America, North-Western and Eastern Europe, Russia and China. The centres of ancient civilizations and especially the Mediterranean regions are not comprised in the geography of coal. The high price of firewood on the one hand and the lack of coal on the other did not allow the transition towards a new energy system in a Mediterranean civilization.⁴⁰

³⁹ The decline of the curve in Figure 2 coincides with economic decline in Britain. See the trend of the British economy described by Ward-Perkins 2005, Ch.V.

⁴⁰ Bresson 2006, 77.

6. AN ENERGY CRISIS?

It is still hard to quantify the rise in population during the millennium spanned by ancient Mediterranean civilizations. While historians do not agree on the figures, they do agree, on the trend of population. In 800 BC, some 20 million people lived around the Mediterranean Sea, whereas in 150 AD the population of the Roman Empire numbered 70 million,⁴¹ although the estimate of 100 million could be equally plausible, given the uncertainty of any estimate for that period. Such a level of population was again attained by the European continent (without Russia), only in the early modern centuries. Although a calculation of the carrying capacity of the Mediterranean world is risky, the estimates proposed above regarding the extent of land necessary to support the population in energy sources do suggest that the rising population put pressure on resources. Data on decreasing returns to labour are, however, scanty and uncertain.

It has been suggested that body size diminished in Western Europe from 150 AD, after a period of rise.⁴² On the topic, however, there is no certainty at all. Koepke and Baten write that 'during Roman times we have more or less stagnating heights'.⁴³ If stature actually diminished, probably it diminished later in Central and Northern Europe (e.g. Germany) than in the Mediterranean regions.⁴⁴

A wider knowledge begins to be available on climate and we can start to speculate on the possible influence of climatic changes on the availability of energy sources. On this topic as well, the evidence is still contradictory, however.

For a long time the rising pressure of population was supported by rising temperatures in the Mediterranean and the whole of the Northern hemisphere, during the *Ancient Climatic Optimum*.⁴⁵ Historians agree on the existence of a Roman Warm Period.⁴⁶ Research on ice carots from Greenland ice core and the ratio of two oxygen isotopes (¹⁸O/¹⁶O) provides a record of ancient water temperature and then climatic oscillations. On this basis changes in temperature have been reconstructed over several million years. Annual changes from the 1st century BC are represented in Figure 2.

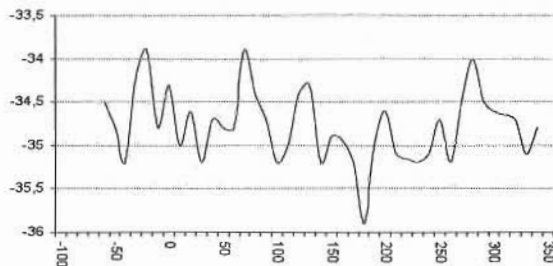


Fig. 2. Oxygen isotopes in the ice carot GISP2 (Greenland glacier ice core) 60 BC–350 AD. Source: Rossignol 2012, 97.

We can see that the two centuries BC were favourable from a climatic viewpoint. Temperatures were high during that period and remained so until the middle of the 2nd century AD. Some historians suggest that, after 150 AD temperatures diminished remarkably, as the curve in Figure 2 shows. Very little, however, is known about the evolution of climate in the Mediterranean.

Rossignol has claimed that 'a remarkable worsening of the climatic conditions' occurred from about 150 AD. The middle of the 2nd century 'witnesses the end of a warm period during which the ratio of the oxygen isotopes had attained levels which would only be reached again in the 20th century'.⁴⁷ The presence in the ice carots of sulphuric acid, dated between 153 and 162, reveals the influence of volcanic eruptions on the fall in temperatures.⁴⁸ Higher temperatures mean that the season for harvesting vegetables is longer; that land can be cultivated at higher altitudes and further North.⁴⁹ Soil porosity rises when temperatures are milder.

The opinion expressed by S.W. Manning is more cautious: 'A range of records indicate that a stable and reasonably positive (warm, and in a number of areas or cases also mainly moist) climate regime was in place for the period from about the 2nd century BC through the 2nd century AD. This

⁴¹ Scheidel 2007, 47.

⁴² This is the opinion expressed by Jongman 2007a, based on data collection by Geertje M. Klein Goldewijk. See also Kron 2005 and 2008.

⁴³ Koepke and Baten 2008, 150.

⁴⁴ Koepke n.d.

⁴⁵ Haas 2006, 147–150.

⁴⁶ Sallares 2007, 19. See also the long-term view in Blender et al. 2006.

⁴⁷ Rossignol 2012, 96. See also Manning this volume, Fig. 8.

⁴⁸ Rossignol and Durost 2007.

⁴⁹ See also Weinstein 2009.

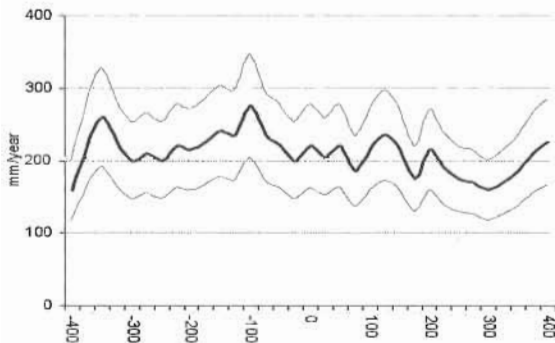


Fig. 3. Intensity of precipitations between 400 BC and AD 400 (and range of error) (mm. per year). Source: Büntgen et al. 2011, 581.

unusual status, reducing some of the typical variability, uncertainty and risks of the Mediterranean climate regime for farming, would have been conducive to the growth of the Roman world. It was also an especially favourable time (warm, moist) for both agricultural and demographic expansion in central and northern Europe.⁵⁰ According to Manning, 'the stability of the previous several centuries ended; agricultural uncertainty and bad years would have increased'. It is hard, however, to specify the turning point towards decreasing temperatures. The 2nd century does not reveal, in his opinion, a clear declining trend.

Precipitation has been reconstructed for the region of Israel⁵¹ and for Germany and Switzerland.⁵² We know that it diminished and the climate became drier when the temperature was falling (Figure 3). In Central Europe, precipitation peaked in 100 BC, but from then on diminished, reaching a minimum in AD 300 (100 millimetres less than in the second century BC). The climate became 'increasingly dry'.⁵³ According to Manning, 'the 2nd to

⁵⁰ Manning this volume.

⁵¹ Orland et al. 2009.

⁵² Büntgen et al. 2011, 581.

⁵³ Schmidt and Grühle 2003a and 2003b.

5th or 6th centuries AD seem to be relatively arid in several areas of the eastern Roman empire, and the indications of less favourable climate conditions further East into central Asia may have been one of the forcings behind the movements of populations that led to invasions/migrations into the late Roman world.⁵⁴

The pressure of population on the energy resources both to provide food (and then widen the arables) and firewood resulted in a decline of the forested areas.⁵⁵ By the end of the Republic, most of the areas of Italy that were accessible to Rome had lost most of their stands of tall trees, but except for some metal-working centres, most places had stabilized their fuel supplies. Patches of eroded land continued to multiply, however, all the way through the high-imperial period of prosperity.⁵⁶ In Spain, 'climate deterioration' would have hampered 'vegetation recovery after fire and exacerbate[d] human impact (deforestation) in general'.⁵⁷ In such cases, because of the need to meet the inelastic demand for food, the livestock and meadows diminish (although for the ancient world nothing certain can be said on the matter). Intensification occurred in agriculture and convertible husbandry spread to support the demographic rise at least in Italy.⁵⁸ For a comparison, in Europe, between 1500 and 1700, the 40 percent rise in population, from 80 to 120 million,⁵⁹ resulted in a 20 percent decrease in agricultural product per capita (that is energy, since the greater part of energy came from the fields).⁶⁰

Population pressure on the energy sources diminished certainly after the Antonine Plague, that spread between 160 and 170 AD,⁶¹ as archaeological wood remains from Central Europe seem to suggest (Figure 4).

By themselves, neither population rise nor climatic changes are necessarily connected to phases of economic decline. Their coincidence can, however, deeply influence the economy and provoke deconstruction and finally collapse.

⁵⁴ Manning this volume.

⁵⁵ See, however, the reconstruction by Kaplan et al. 2009. See also Ruddiman and Ellis 2009.

⁵⁶ Harris 2011, 139.

⁵⁷ Kaal et al. 2011, 172.

⁵⁸ Forni and Marcone 2002.

⁵⁹ Russia is included in these estimates of population.

⁶⁰ Kander et al. 2013.

⁶¹ See especially I. O. Cascio 2012.

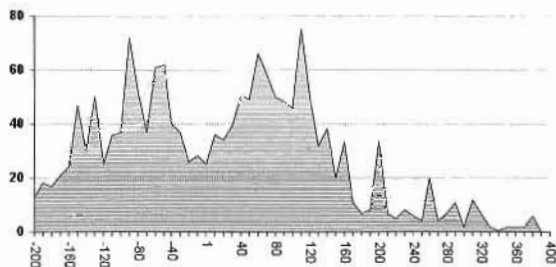


Fig. 4. Estimates of forest clearance in Central Europe (Germany, North-Eastern France) from archaeological wood remains 200 BC–400 AD (decadal data; any point of the diagram represents the intensity of the felling). Source: Büntgen et al. 2011, 580.

CONCLUSION

The energy system of ancient Mediterranean civilizations was the same as that of all agrarian societies. Despite the increase in useful knowledge and the extensive development of the agrarian energy basis, supported by a favourable climatic phase, this system was finally unable to support the increasing needs of the rising population (as always in agrarian civilisations). If we follow the economic approach by the classical economists, rephrased by E.A. Wrigley with particular reference to energy, an increasing pressure on the resources by the rising population would have been followed by decreasing returns and then diminishing energy availability, after some centuries of rising population. Data showing a clear economic trend for the first centuries of the Empire are almost entirely lacking, but an unfavourable climatic phase, beginning probably, but not certainly, in the second half of the 2nd century AD, contributed to a decline.

Much later, during the *Little Ice Age*, in the early modern centuries, the reaction to a similar crisis was a much wider use of coal.⁶² This main change developed in England since the 16th century. Then, in the 18th century, the steam engine began to interact with the new, rising input of energy. This

interaction initially began to involve the Central and Northern European regions and subsequently also the regions far from the centre of the great change then in progress. The combination of changes in power and energy was the basis of modern growth. Just as in many other pre-modern societies, the structure of the energy system prevented ancient Mediterranean civilizations from following a similar path. Ancient growth found in its energy basis a main constraint to its further economic progress.

⁶² The topic is discussed in Malanima 2010 and 2011.

APPENDIX

Estimates of Energy Consumption in the Early Roman Empire

A wider analysis of per capita energy consumption in the early Roman Empire is presented in Malanima (forthcoming). The topic of energy consumption in pre-modern economies is also discussed in Malanima 1996, 2006, 2009, 2010, 2011 (www.paolomalanima.it).

As seen above (§ 1–2), sources of energy of pre-modern, agricultural economies are the following:

1. food;
2. fuel (almost always firewood);
3. fodder for working animals;
4. water and wind power.

1. Food

Food consumption has always been the most stable energy carrier ever exploited since the beginning of the human species. In the following diagram (Figure 5), I report the series presented by Jongman (2007b, 599), on calorie consumption in present day populations. Taking into account the age structure in Roman antiquity, with more young people than today, the range of 2–3,000 calories seems plausible. Considering yields per hectare, to cover the needs of a family of 5 people, about 5 hectares were necessary, including fallow lands. Thus a family needed between 2.5–3.3 hectares of cultivated land (excluding fallows); i.e. from half to two-thirds of a hectare per person (for data on yields, and soil per capita necessary to satisfy food demand, see Forni and Marcone 2002, on agriculture in Roman Italy).

2. Firewood

As said in § 1, firewood consumption depends on temperature and industrial use. One kg. of wood can be seen as the lowest possible level of consumption (as also stated by Harris 2011a; see also data in Pireddu 1990, 27). Although hard to quantify, firewood consumption was low where temperatures were high and high where temperatures were low (see, for instance, data in Warde 2006, referring to early modern Europe). If, to simplify, we assume that in a Mediterranean climate, each individual consumed 1 cubic metre of wood per year, that is 625 kg., including industrial uses as fuel (1.7 kg. per day), this amount of wood could be provided by the yearly growth of half a hectare of forest (Chierici 1911, 232–233). Assuming that the population of the Roman Empire in around 165 AD was 70 million inhabitants for an

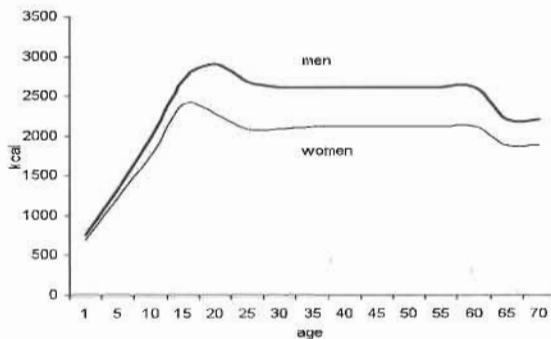


Fig. 5. Food consumption by modern populations according to age (kcal.) Source: Jongman 2007b, 599.

area of 3,800,000 km², and that every inhabitant consumed 1 cubic metre of firewood (including wood from prunings), then the total requirement was 70 million cubic metres. It could be provided by a wooded area of 350,000 km², or 9–10 percent of the total inhabited surface of the Empire. With a population of 100 million inhabitants, the wooded area rises to 500,000 km², or about 13 percent of the total. A city such as Rome, with 1 million inhabitants in the age of Augustus, needed 50 km² of forest to cover its needs.

As to industrial consumption, we can only provide some calculations from what we know about the output of metallurgy. Let us assume that iron production was between 80,000 and 160,000 tons per year (cf. Harris 2011a) and, at the lowest, a consumption level of 30 kg of firewood (transformed into charcoal) per kg. of iron (Smil 1994, 144–156). Charcoal, known in Egypt as early as the 3rd millennium BC, was widely used in Greek-Roman antiquity (Wikander 2008, 138). For the production of 80,000 tons of iron, the quantity of firewood would thus be 2,400,000 tons (converted into charcoal). In cubic metres, the requirement was 3,840,000 (assuming 625 kg. per cubic metre, and then dividing 2,400 million kg. by 625). With a yearly productivity of half a cubic metre per hectare of forest, in order to produce 3,840,000 cubic metres, 1,920,000 hectares or 19,200 km² were necessary. Assuming iron output being twice as high, the need amounts to 38,400 km² of forest. This

area is only 5–10 percent of the total forest required by the population for heating and cooking. As said before (§1), other industries (such as pottery, glass and tile production) and services (such as baths) exploited wood. An estimate is, in this case, impossible. Fuels different from firewood represented a negligible share of the total. Thus, our estimate for a Southern, Mediterranean civilization such as the Roman Empire is between 1 and 2 kg of wood, that is 3,000–6,000 calories per capita per day.

3. Fodder

The estimate of fodder consumed by draft animals is more complex. From the viewpoint of energy, an ox or some other working animal is like a machine. It metabolizes vegetables to accomplish a task. In order to establish the average consumption in energy sources per head, the input of energy by a draft animal must be divided by the family members that exploit it. We know that improved fodder management and nutrition determined a remarkable increase in the size of animals during Graeco-Roman antiquity. Ley farming and meadows supplied animals with better fodder than in the late Middle Ages and early modern times (Kron 2000). Oxen were taller and heavier than in Medieval and early modern Europe: about 400 kg instead of 2–300 (Kron 2002 and 2004).

We can establish a ratio between working animals and population in ancient Mediterranean civilizations from the technical relationship suggested by ancient agronomists between land and working animals. In the 1st century BC, Varro recalls the opinions of Cato and Saserna about the need of a yoke for every 80–100 iugera (20–25 hectares) (*On agriculture* 1.21–22). Since a yoke is composed of two oxen, the relationship is therefore a working animal per 10–12.5 hectares. A century later, Columella tells of two yokes of oxen for a farm of 200 iugera (or 50 hectares) (*On agriculture* 2.12.1–7). Again we find a ratio similar to that suggested by Varro and relatively close to the animal-land ratio found in early Modern Europe. Since a peasant family required a farm of about 3–5 hectares to support its living (as shown in §1 of this App.), we could divide among the 10–15 members of two average families endowed with a farm of 3–5 hectares each, the calories from fodder consumed by oxen (25–30,000 kcal per animal per day) and we would obtain the result of 1,700–3,000 kcal. per head. We would have to add to this estimate horses (on which see Vigneron 1968), mules, donkeys and camels, and we would also have to include urban inhabitants (excluded from the previous draft animals-peasant families ratio) in the denominator of our ratio. All things considered, a range of 1,000–2,000 calories per day per capita seems plausible.

4. Wind and Water

The only possibility of estimating the consumption of water and wind power is to start from power (work done per unit of time - 1 second-). In the case of a large sailing ship, with a carrying capacity of 400 tons, a rare example in the ancient world, where the majority of sailing ships were below 100 tons (Greene 1986, 26), a relationship existed between tonnage and power. The power of such a ship (400 tons) was about 50 HP (Malanima 2006). Assuming (absurdly!) that this power was exploited fully for 24 hours and 365 days per year, energy per year would be 438,000 HPH (Horse Power hour is a measure of energy), that is, 770,000 kcal. per day. We would now need a plausible ratio between ships and boats on one hand and population on the other. Even assuming the ratio existing in early modern Europe to be correct, the result would be less than 1 percent of the entire energy consumption per capita.

The watermill was the most powerful engine existing on land. Generally its power did not exceed 2–3 HP, although examples of big mills (Munro 2003) or the combination of several mills in powerful sets of engines are not lacking (Brun 2006; Wikander 1979, 2000 and 2008). The mechanical work produced by a watermill endowed with the power of 2 HP is about 64,749 kJ. (15,000 kcal.) per day, and since a man consumes 2,550–3,000 kcal. per day as food, consumption of gravitational energy by a watermill is 6 times the energy consumption of food per capita. In late medieval and early modern Europe, a ratio existed between watermills and population: 1 watermill every 250 people. Otherwise stated, any small village of 50 families had its own mill (on the topic Makkai 1981 is important). If we divide a mill's energy consumption by 250, the result is 60 kcal. Certainly, the use of mechanical energy to grind cereals was a remarkable achievement of ancient civilization. Its contribution to the energy balance was, however, modest in mere quantitative terms. Although we do not know the inhabitant-watermill ratio in the ancient world, and even allowing for the existence of the same late medieval ratio, which seems too high for antiquity, as early as the first centuries of the Roman Empire, the result is that the contribution to the energy balance was indeed modest (Reynolds 1983; Lo Cascio and Malanima 2008).

Let us consider that previous calculations on mills and ships assume full-time work (24 hours per day), which is implausible. Contributions to the energy balance assuming more realistic working time imply a reduction of the available energy per head.

The Estimates by Ian Morris

Different estimates of energy consumption have been provided by Ian Morris (2010a and 2010b). According to Morris (2010a, 28), the sources to be taken into account for a calculation of energy consumption (including the ones used in modern economies) are the following:

Food (whether consumed directly, given to animals that provide labour, or given to animals that are subsequently eaten);

Fuel (whether for cooking, heating, cooling, firing kilns and furnaces, or powering machines, and including wind and waterpower as well as wood, coal, oil, gas, and nuclear power);

Raw materials (whether for construction, metalwork, pot making, clothing or any other purpose).

We can see that there is a similarity between this list and the sources taken into account in this paper. However: 1. I do not include feed 'given to animals that are subsequently eaten', since it is already included in the 2–3,000 kcal. of food for humans (and it would be a duplication of the same source in our calculations). These animals certainly put a high pressure on carrying capacity. If agricultural produce is not consumed directly by the population, but consumed by animals which are then eaten by the humans, the pressure on land is higher. In any case those animals are only used as food and are not exploited in agriculture or transport. They are part of human food; which enters the energy balance. As a consequence, I include only feed for working animals; 2. it is not clear how Morris computes the contribution by wind and water power; 3. raw materials cannot be considered as energy carriers and are not included in my estimates (or in those of the International Energy Agency or the US Energy Information Administration). Morris follows, however, Cook 1971, who includes 'vegetable fiber', which brings 'solar energy into the economy through photosynthesis' (134). See also Cook 1976, 51 and 135. Raw materials, however, are not used as providers of energy. Firewood, is also generated by photosynthesis, hence when used as an energy carrier I include it in my calculations. When timber is used as raw material for construction, it is not included, despite being produced by photosynthesis. It is not an energy carrier in this case.

The results by Morris are quite different from those presented in the previous pages. In the following Table 2 some data are reported from two series presented by Morris (2010b, 628).

Table 2. Energy consumption in advanced regions of the West and East according to I. Morris. 8000 BC–2000 AD (thousands of kcal, per capita per day).

	West (000)	East (000)
2000	230	104
1900	92	49
1800	38	36
1700	32	33
1500	27	30
1000	26	29.5
200 AD	30	26
1 AD	31	27
200 BC	27	24
8000	6	5

Source: Morris 2010b, 628.

Around 2000, the average world energy consumption was 50,000 calories per day. According to Morris' estimate, in 200 BC some parts of the World already exceeded this level even without fossil fuels.

In both works by Morris (2010a and 2010b), previous data (reported in Table 2) for the year 2000 actually refer to the most advanced countries in the West (USA) and in the East (Japan). In addition, data for previous years refer to 'the most developed core within the West' (Morris 2010b, 42), whose borders, however, are not clearly defined. In any case, Morris' results are too high. In 1800, according to recent research, energy consumption in Western Europe (a highly developed part of the globe) was not 38,000 kcal. (as maintained by Morris), but about 15,000 (average for Sweden, Norway, The Netherlands, Germany, France, Spain, Portugal and Italy) (Kander et al. 2013 and data published in Gales et al. 2007). In 1900, for the same countries of Western Europe, the average was 41,500 kcal. per day per capita, and not 92,000 (as in the previous Table 2). In England it was 95,000. Morris' estimate for 1900 is only plausible if by 'West' we refer only to England. As we see, data for the Roman Empire are also quite different from ours. Even if we take the most advanced part of the Roman Empire, Italy, in 1861, that is, the year of the Unification of the country, energy consumption per capita was 11–12,000 calories (Malanima 2006), less than half the estimate proposed by Morris for the West (31,000) in 1 AD.

Energy intensity represents the ratio between energy consumption and GDP. In Western Europe from 1800–1820 it was 12–15 Megajoules per 1 dollar (1990 international Gery-Khamis dollars), when per capita GDP was 1,200

dollars (according to the series by Maddison 2007, in 1990 international Geary-Khamis dollars PPP). If we assume the very high estimate of 1,500 dollars for Roman Italy (taking into account that recent estimates hardly exceed 1,000 dollars, as shown in Lo Cascio and Malanima 2009 and forthcoming), the resulting estimate of energy intensity, taking Morris' estimate of 31,000 kcal. per head per day (and then 11,315,000 kcal. per year, or 47,342 Gigajoules), is 32 Mj. per dollar, and thus more than twice that ascertained in 1800 for Western Europe. With a GDP per capita of 1,000 dollars in the early Roman Empire, the implied energy intensity becomes 47 Mj. per dollar. For a comparison, in 2000, World energy intensity was 11.5 Mj. per dollar (1990 Geary-Khamis int. dollars) and in Europe it was 5.5 Mj. per dollar.

Vaclav Smil (2010, 107–113) proposed estimates of energy consumption in ancient Rome that are far lower than those by Morris. Here is the comment by Morris on Smil's views: 'Roman total energy capture would be somewhere between 4,600 and 7,700 kcal/cap/day [according, that is, to Smil's calculations]; if we assume that roughly 2,000 kcal/cap/day of this was food (which means ignoring the archaeological evidence for relatively high levels of expensive calories from meat, oil, and wine), that leaves just 2,600–5,700 kcal/cap/day to cover all other energy consumption'. To justify this estimate, Smil suggests that Roman fuel use was just 180–200 kg. of wood equivalent per capita per year, or 'roughly 1,750–2,000 kcal/cap/day'. Smil's estimate of firewood consumption certainly seems too low. On the whole, however, Smil's estimates are closer to mine than are those by Morris.