McDONALD INSTITUTE CONVERSATIONS

Fuel and Fire in the Ancient Roman World

Towards an integrated economic understanding

Edited by Robyn Veal & Victoria Leitch

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with contributions from
Jim Ball, H.E.M. Cool, Sylvie Coubray, David Griffiths, Mohamed Kenawi, Victoria Leitch, Archer Martin, Ismini Miliaresis, Heike Möller, Cristina Mondin, Nicolas Monteix, Anna-Katharina Rieger, Tony Rook, Erica Rowan, Robyn Veal, Véronique Zech-Matterne

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Preface

This book arises from a conference held at the British School at Rome, and the Finnish Institute in Rome, in March 2013, entitled Fuel and Fire in the Ancient Roman World. The conference represented the first real attempt to try to bridge the gap between 'top-down' generalized models about Roman energy consumption (itself, still a relatively new area of research), and research carried out by artefact and environmental specialists. In many ways it exceeded our expectations, although it probably raised more questions than it answered. As fuel is used in many different domestic and industrial contexts, the papers were very heterogeneous; some presenters came from a strong archaeobotanical background, which is a central area for fuel research, while others came from social, technical and economic spheres, opening up the discussion beyond archaeobotany. Some papers presented more 'qualitative' rather than 'quantitative' results but, as a new research area, this was inevitable and qualitative evaluation can provide the framework for approaching quantitative studies. Nevertheless, useful quantitative beginnings are proposed in a number of papers. Although focused on the Roman period, the research often extended beyond this chronological span, to help contextualize the results.

We gratefully acknowledge the support and assistance of the British School at Rome and the *Institutum Romanum Finlandiae* (Finnish Institute of Rome). In particular we thank Professor Katariina Mustakallio, then director of the *IRF*, for generously hosting the conference lunch on the final day. The financial support of the Oxford Roman Economy Project, through Professor Andrew Wilson, and a significant private donation from Mr Jim Ball, former Commonwealth Forests Chairman (administered through the BSR Rickman Fund) allowed speakers' travel, accommodation and subsistence costs to be covered, as well as a contribution towards publication costs. Professor Wilson and Mr Ball both provided much appreciated moral support and intellectual input, acting as our major discussants. The McDonald Institute for Archaeological Research, through its Conversations series, also helped fund publication. Professor Graeme Barker (McDonald Institute director to September 2014), Professor Cyprian Broodbank (current director), Dr James Barrett (current deputy director) and Dr Simon Stoddart (former acting deputy director) all provided advice and guidance over time. This was much appreciated. Dora Kemp provided initial advice on manuscript preparation, and after her untimely death, Ben Plumridge took over the practical side of production. Maria Rosaria Vairo, then a Masters student of the University of Lecce, and Dana Challinor, a doctoral student at the University of Oxford, provided significant voluntary support during the conference and we thank them both profusely. Robyn Veal would also like to acknowledge the long-term financial and intellectual support of the Department of Archaeology, University of Sydney, through much of her early work on fuel. This led to the opportunity of a fellowship at the BSR, and the idea for this conference. The feedback from reviewers has greatly improved the book.

Robyn Veal & Victoria Leitch

Chapter 1

The history and science of fuel and fire in the Roman Empire

Robyn Veal

The Romans had strong technological skills that were applied to all aspects of life, from public to private domains, and most required the employment of fuel. Architectural advances were facilitated by waterproof cement and the use of higher-level mathematics to build large domes; road and shipbuilding became highly developed; and water management through the construction of large-scale aqueducts fundamentally changed the landscape and the economy. In manufacturing, metals, ceramics and glass, already present in the ancient world well before the Romans, reached new heights of refinement, as well as higher levels of mass production. On an elite domestic level, cooking became both an art and an expression of *otium*. Fashion dictated the demand for the colouring of new fibres, and the production of ornate jewelry and personal effects made of many types of materials. The artisanal classes and the poor also needed wood in its various forms in order to live. Tools were essential on farms, and for use in some industries. Most agricultural activities used wood for stakes, and as fuel for various purposes (such as heating in olive presses, or making lime). Food was sometimes smoked. Everyone needed to keep warm in winter.

All of these processes involved the supply and consumption of fuel and the use and control of fire. Fuel and fire touched the life of every Roman, every day, and yet our exploration of this topic has been fairly limited to date. We have examined the historical sources in the past, but where these are discussed without inclusion of much science (especially ecology and climate), or appropriate use of archaeological evidence, they can lead to quite inaccurate conclusions.[1] As a prelude to the following chapters, the discussion here overviews the relative importance fuel played in the function of the economy, and provides some technical background to the nature of fuel in the Roman Empire.[2]

Characterizing the importance of fuel in the economy

The ancient GDP

We are unable to estimate the percentage of the ancient GDP that fuel may have represented, but even in the modern day, fuel has represented somewhere between 10 and 15 per cent of the GDP of the United States (Veal 2013). If we accept the view that agricultural and other parts of the economy were less efficient in Roman times than at present, fuel may have constituted 20 per cent or even more of the GDP. This figure does not imply that the total value of the ancient Roman GDP has been underestimated by scholars, but rather that the finer details of the make-up of the ancient GDP are yet to be fully elucidated.

A survey of major types of fuel in the ancient world: wood and charcoal

Wood was the most important and commonest fuel in the ancient period, and is observed archaeologically as fuel waste in Europe and most of the Mediterranean, especially where woodland was common. Petroleum-based fuels were little understood, although they were occasionally used when found. We especially know of coal used in the later Roman period in Roman Britain, where it has been found mixed with charcoal, especially for iron smelting (Veal 2012a). Romano-British coal did not come from sub-surface mines, but was mostly recovered from surface deposits. Similarly, pitch and other liquid tarry substances were known in the east but ancient sources do not document these extensively, and proof of their use as fuel cannot easily be detected archaeologically, as they burn to completion.

Both raw wood and raw wood made into charcoal were used for domestic and industrial purposes. When charcoal was consumed, naturally a proportion of raw wood was required to make the charcoal. The ratio for carrying out this conversion was (and still is in modern developing wood-dependent countries) quite variable, and is based on a number of factors including ambient conditions, skill of the charcoal-maker, and sometimes, intended use of the charcoal.[3] Wood, often cut to measure, was piled into heaps and covered by ash remains from a previous charcoal burn, plant waste and sometimes mud. Alternative means of making charcoal also included making a pit for the wood, and covering it with a metal sheet, or even 'rough' fabrication in a fire, before use in small-scale smelting or smithing operations. The covered stack or pit of wood was then 'charcoalified': in the absence of oxygen, most water and organics are driven off with heat, leaving a mostly carbon-based product (as opposed to combustion, where the presence of oxygen causes complete consumption of the wood to produce heat, ash and water) (Chabal et al. 1999). Production 'efficiency' of charcoal ranged potentially from 4 or 5 kg raw wood to make 1 kg of charcoal, to a very inefficient 10 or even 20 kg raw wood to make 1 kg of charcoal. It is reasonable to expect that skilled Roman charcoal-makers were 'efficient', although to produce charcoal of a very high quality (i.e. high carbon content), long charring was required (thus reducing the resultant charcoal weight, an apparent reduction in efficiency, necessary to increase the carbon content). It appears from work in Pompeii (Veal 2012b, 2014), that charcoals for domestic use[4] were of a moderate quality with some organic volatiles left in the charcoal to facilitate ignition of the fuel in the kitchen, while charcoals used in metal smithing may have been of much higher quality (denser, and with a higher carbon content). These broad observations correlate with modern ones made for wood dependent developing countries (Schenkel et al. 1998), and laboratory work on archaeological charcoal is ongoing.

Non-wood fuels

Almost anything organic can be used for fuel (or turned into charcoal for that matter). Agricultural wastes of all sorts (mostly in the raw state) were routinely consumed, especially in places where wood was scarce, i.e. any part of the empire where poor soils or poor rainfall predominated, such as Greece, parts of the East, and those parts of Africa furthest away from the coast. One of the first studies on chaff looked at its use in arid and semi-arid zones (van der Veen 1999). Some of the following chapters (Leitch, Martin, Möller & Reiger and Kenawi) elucidate valuable ancient and modern ethnographic examples, especially in the case of ceramic production on the African continent. Even in places where wood was common, non-wood fuels have also been consumed when available. Of all of these, olive pressings (often referred to as 'pomace'), were the most useful in terms of calorific value (see Coubray et al. and Rowan, this volume). The volume of olive pressings available varied geographically and seasonally, and so while available were precious if used as fuel; they could also be used as animal fodder and even fertilizer (both in limited quantities).

Other examples of non-wood fuels include: seaweed (Griffiths & Harrison 2011); peat, especially in wetter climates – but for an Italian example see Peña (2013); and animal dung, the detection of which in the archaeological record is still a challenge (Lancelotti & Madella 2012). Recognizing animal dung as fuel requires careful attention to field collection of archaeobotanical remains, as well as a recognition of seed assemblages inside the dung. Its use as fuel means less is available for fertilizing soils. Animal bone has also been detected as fuel but more instances are recorded for prehistoric periods (Beresford-Jones et al. 2010; Théry-Parisot 2002). This list is not exhaustive.

Lighting: lamps and torches

The commonest form of Roman lighting was the oil lamp, which came in a large range of styles and sizes. Olive oil was the main fuel, although other vegetable oils and animal fats were also used. Griffiths (in this volume) focuses on this topic in detail. Evidence ranges from ancient historical records to the numerous archaeological ceramic and less common metal lamps. Indirect archaeological evidence includes hooks in walls and niches in which lamps could be installed, both inside and outside buildings.

In addition to lamps, torches were used. The literary and artistic evidence is summarized by Smith (1875).[5] Torches were 'formed of wooden staves or twigs, either bound by a rope drawn about them in a spiral form… or surrounded by circular bands at equal distances…. The inside of the torch may be supposed to have been filled with flax, tow, or other vegetable fibres, the whole being abundantly impregnated with pitch, rosin, wax, oil, and other inflammable substances.' The Romans knew of phosphorus, and also could make complex torches of sulphur and lime (which burn for longer). These topics have been little studied, beyond the literary and artistic evidence such as the wooden staves and the types of flame depicted. Archaeological preservation would be rare (of the torches themselves), although some buildings in Pompeii appear to have niches and/or iron rings attached outside at a height and location that may suggest their function as part of a lighting installation, as mentioned above. Whether individual cases were for torches or lamps is a matter needing further investigation.

Calorific potential and efficiency of fuel consumption

Each type of fuel has an intrinsic heat value ('calorific potential'). In general terms, if an 'inferior' fuel is used, more of it will be required, all other factors being equal, than if a 'superior' fuel is used, but caveats apply. Some processes require charcoal as it produces a more continuous heat, providing greater temperature stability, whether for low (such as cooking a delicate custard), or high temperatures (metal-working). Charcoal is essential in some high-heat technological processes (*c*. 1100 °C) as this temperature is difficult to achieve with raw wood in a consistent manner (for example in iron-smelting and, usually, smithing). The charcoal is also consumed as part of the chemical reaction of reduction in smelting. However, even lower calorific potential fuels have their uses: straw, for example, can be used to help raise the temperature quickly, although it will not produce a sustainable heat. Table 1.1 shows the approximate relative calorific potentials of different fuel types.

We can only estimate relative values because different types of raw or dried peat, wood, pomace, etc., will vary slightly in their calorific potentials. Taking raw wood as our standard value of '1', 'good wood' means a typical hardwood such as oak or ash. 'Charcoal' denotes typical hardwood charcoal. Table 1.1 shows that 'charcoal' is nearly double the heat potential of 'good wood'; that 'olive pomace' is a valuable fuel; and that our modern addiction to fossil fuels is easily comprehended. It should be noted that just as almost any type of organic material can be used as fuel, and most can be made into charcoal, differing organic materials result in charcoal of slightly varying qualities.[6] However, once made into charcoal, calorific potentials of charcoals of different origins do not vary as much as the calorific potentials of their original materials (so, for example, it is not correct to infer that olive pomace, a high calorific fuel, once made into charcoal, will produce a lot more heat than any other type of charcoal).[7]

Table 1.1. *Approximate relative heat values of different fuel types, drawn from a range of sources.*

Peat (dried)	0.8
Poultry litter	0.8
'Good Wood' @ 20% moisture content (air-dried)	1
Olive pomace (skin, pips, pulp)	1.3
Charcoal	1.8
Coal (average quality)	2
Oil (fossil fuel) or LPG (liquid petroleum gas)	2.5
Coal (anthracite)	3

Besides heat potential, to understand fuel consumption we also need to understand 'heat yield'. By this we mean the amount of potential heat in a fuel that actually ends up employed in the process intended. Different technological situations differ in their efficiency of fuel use, and of course, the less efficient a process, the more calorific potential is lost to the air (and not applied to the process intended), and therefore the more fuel will be required to get to a particular result. In open fires, about 10 per cent of the calorific potential actually makes it into the food being heated/cooked, or the industrial process being undertaken. Enclosed tripods reach perhaps 30 per cent efficiency (so, moving from the prehistoric to the historic periods, man's approaches to cooking became more efficient by using stone surrounds for fire, and/or tripods of ceramic and then metal). Oven efficiency, depending on the oven, may have ranged from 30–50 per cent;[8] and for kilns, a range of 40–80 per cent may be inferred, depending on the kiln type and build, and in particular whether it was a continuous use kiln (more efficient), or single use.

Factors affecting the wood supply

A range of factors affected the wood supply, from ambient ecological conditions to land ownership, silvicultural practices, intended cultural uses, transport and pricing. Geology, topography, climate and soils are the base determinants of where different plant types grow. Below appears a summary of these factors. A more detailed discussion may be found in Veal (2013). Italian growing conditions range from coastal and inland flats to steep mountains and islands, with soils enriched by their recent evolution in geological time through volcanic activity. We generalize climate to be 'Mediterranean' (hot dry summers, wet winters), but micro-climates were worse, and better than this, and the provinces varied greatly.

Geology

There are radical differences in geology between those parts of the empire located on or near volcanically influenced crusts (e.g. Italy) and those removed from these areas (e.g. Roman North Africa, Egypt and Greece). Italy's fertility has been sung by the ancient writers, and proven in geological and macrobotanical analyses. Egypt's soils and water supply were relatively poor except for those associated with the Nile delta and its seasonal flood. This alluvial area was and is large, making the province the breadbasket of Rome for many years. Outside this area though, in much of the African continent, desert prevailed. Greece has always had mostly poor soils, and in many places, much less rain than Italy (Rackham 1982). These base ecological conditions created greater challenges for timber provision in Greece (and Egypt), and much timber was imported, although local scrubland and limited woodland seemed to have provided sufficient fuel, which at least in the Greek historical sources was made into charcoal and transported by donkey into town. Greek villagers, however, were noted for sharing cooking facilities (thus saving fuel), rather than always cooking individually at home (Bresson 2016, 72–3).

Topography

Large mountains block inflowing warm and wet air from the sea. In the case of Italy with its raised central peninsular spine, rainfall is more abundant in the centre, i.e. in the Campanian Apennines (modern range 1000–1700 mm p.a.), than at the coast (modern range 700–1000 mm p.a. on the Campanian coast) (Costantini et al. 2013). Steep inclines can tend to lose topsoil with rainfall, making areas of even apparently fertile soil less suitable for growing anything other than scrub. Steep inclines also influence silviculture practices (see below).

Climate and micro-climate

Forest growth is greatly affected by climate, but broad regional 'climate' characteristics may be quite different to those observable at micro-climate (i.e local city/state) scales. Variation in the so-called 'Mediterranean' climate was (and is) as much as 30 per cent (in terms of precipitation and temperature) from place to place. The Roman 'warming period' (*c.* 150 BC to second century AD) allowed agriculture in more marginal areas, and was a major factor in bringing about economic and agricultural stability at the time (Büntgen et al. 2011; Harper & McCormick 2018; McCormick et al. 2012). Altogether, climate records show a broader stability of climate for the millennium of Roman dominance, than time periods either side of it. However, even within the Roman period, climate varied. Harper & McCormick's overview of Roman climate is particularly useful in that it explains all of the different proxies that go into estimating past climate, their validity (especially in the Roman period), and the nuances of various results from different areas in the Roman Empire. Data types vary from those which may be resolved broadly (e.g. pollen), to those that can be resolved by decade and even by year (e.g. tree rings). Glacier retreat/advance, speleothems, hydrological changes and many other proxies exist. They reflect the Roman world to a larger or lesser extent, partly depending on distance from the empire (e.g. glaciers were not found in Roman territory but their changes are still a useful correlate for other proxies). We know ice cores some distance from Rome reflect chemical changes in the metal ages (particularly in the Roman period), due to upper atmospheric long-distance aerial transport of smelting chemical products. This global phenomenon, as well as that of the ocean currents, are large-scale drivers of climate, and lead us to speak of regional and inter-regional climates. Intuitively we understand that in the Mediterranean there is a north/south divide, but the east/west divide is also distinctive, and even sub-regions within an area may vary due to geographical permutations. Climate is now considered at the broadest level to be primarily influenced by solar radiation and volcanic activity. Volcanic and solar radiation 'forcing' appear to precede climate changes, which in themselves appear to precede mass population movements and social instability through human history (these were/are not the only drivers of change of course, but socio-economic changes have already been well covered elsewhere in the overall debate).

Volcanoes reduce solar radiation reaching the Earth through the dust and gases that arise from eruptions. Size, frequency and types of eruption (whether highly explosive and producing lots of particulate matter, vs gentle eruptive) determine how much volcanoes may limit sunlight and reduce regional temperatures. Solar radiation is also independently affected by the sun's own output (solar 'flares' increase radiation). Solar changes affect large oceanic currents and upper atmosphere movement and have a subsequent inter-regional bearing. It is notable that we lack sufficient proxies (yet) to be able to say much about Roman North Africa and some parts of the southern Mediterranean. We also have a continuing difficulty of relating climate changes and chronology tightly to archaeological and historical records (and as already stated, we cannot ignore the socio-economic factors of change). A major future challenge is to integrate larger-scale climate changes and smaller patterns of regional weather anomalies into the already well-discussed socio-economic factors.

In ancient studies, when environmental factors are proposed as significant agents in influencing human behaviour, some modern scholars have immediately made accusations of 'environmental determinism.' We know now that environment is a large determinant of the base conditions of life. The degree to which natural environmental changes dominate or influence human behaviour cannot easily be ascertained (and vice versa). Hypotheses in this regard have been made in a general sense, but we need more, and more detailed records of all types (Manning 2018). We can generally correlate colder periods (e.g. the Little Ice Age) with drier conditions, and warmer ones generally with wetter conditions, but this does not always hold (e.g. in the Sahara). Occasionally even in Europe the opposite patterns of expected precipitation apply in small areas.

Land ownership and use

In land use the Romans, as other cultures, could significantly alter fertility by improvements to poorly drained areas (which could then be brought into cultivation), as well as over-exploitation of hilly areas (which resulted in loss of topsoil). Soil fertilization was carried out using animal and plant waste where available, in addition to other strategies such as fallowing, and inter-cultivation of nitrogen fixing crops (especially legumes, such as the famous bean, *Vicia faba*). Land ownership by the emperor, the state and the elite dominated access to forests, with *ager publicus* diminishing over time, presumably making access to fuel by the poor more difficult and/or expensive (although the matter has not been thoroughly explored). Roman emperors valued timber for ship building and construction in particular, especially conifers such as cedar (*Cedrus libani*) and silver fir (*Abies alba*), but these markets and the extent to which they were coveted and protected should not be confused with the fuel supply, although timber waste can end up as fuel (see for example, Harris 2017; Moser et al. 2016; Veal 2017a, 2017c, 2018).

Silvicultural practice in the Mediterranean

Silvicultural practice may in part be viewed through characteristics of archaeological charcoal sections (see an example in Figure 1.1, which is a cross section of a young oak branch). From the cross section a charcoal specialist can identify wood structures, the most important of which are tree rings (one for every year of growth), vessels (to conduct water and nutrients from roots to crown) and rays (to conduct water and nutrients from the core to the outer growing edges). Young (small branches) have fewer rings, and smaller vessels, and often sections of whole small branches may be preserved. Observation of many small–medium branches of consistent diameter – suggests (but does not prove) coppicing or other intensive woodland management. Other information is gained from historical sources and preserved artefacts. These together tell us that the Romans used two-man saws, axes and other woodland management tools, much like those of today (except without electricity!) (White 1967, 1975). While 'coppice', small diameter, uniformly

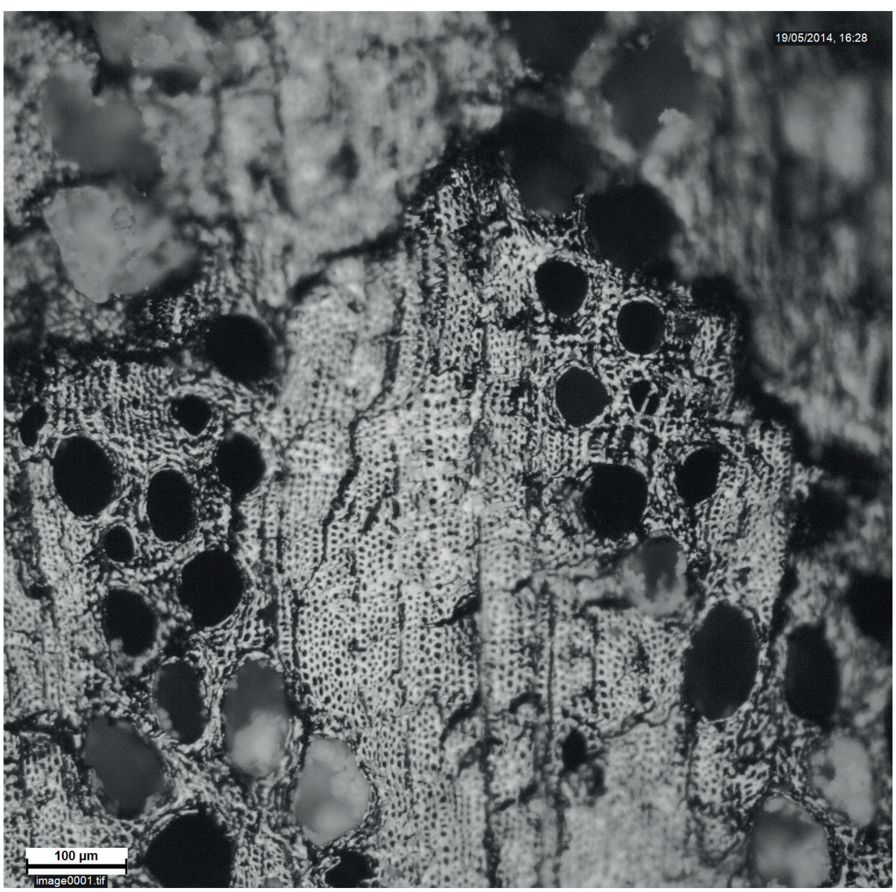

Figure 1.1. *An example of a microphotograph of deciduous oak (cross-section at × 40) from Ostia synagogue (late Roman) (photo Veal).*

Figure 1.2. *Modern 'smallwood' (or coppice) being taken to market in the Sarno valley, Campania (photo Veal).*

cut wood, is often presumed to be the main source of fuel (Figure 1.2 shows a modern example on the way to market), the steepness of the mountains suggests maintaining fencing for satisfactory coppice production may have been difficult, if not impossible, in mountainous parts of Roman Italy. Strategies such as pollarding (cutting above animal grazing height), or indeed clear felling (and sorting), may have been more common in these areas. These differing arboreal management strategies are sometimes difficult to observe in the archaeological charcoal. Care must be taken not to project common strategies in one country (Roman Britain) with those found elsewhere (Roman Mediterranean), despite significant commonality of wood species. Grove & Rackham (2001) provide a detailed overview of the woodlands of the Mediterranean and the various woodland management strategies in different regions.

There is good evidence that charcoal of different qualities was produced for domestic, as opposed to industrial use. In the House of the Surgeon at Pompeii, strong evidence for a first-century BC smithy attached to the villa was found (structures and iron waste), and the associated charcoal was of a much denser, older wood, compared to that of the remains found elsewhere (Veal 2012b, 27, 2018). This pattern of industrial use was also observed in the charcoals of the Porta Stabia area (Veal, unpub.). Coppice production (cutting of wood at the base, so multiple stems regrow), dominated in Roman Britain, for example, and across much of Roman Europe. Small diameter woods also dominate assemblages from more arid areas (those of steppe and maquis vegetation types) although these do not always represent coppice production. Maquis woods, whilst scrappier and sometimes difficult to collect (due to spiny or noxious wood characteristics), were of equal, if not greater calorific potential than wood produced from larger-scale coppice production. A detailed overview of the history of wood fuel in the Mediterranean is found in Grove & Rackham (2001).

Deforestation

We may infer that as the Roman period progressed from the Republican to the Late Antique period, and sophistication of technology advanced, kiln-based manufacturing processes increased, and fuel efficiency also probably improved. Higher temperatures (and finer control of these) were required to manufacture, for example, red-slip ware (*c*. 1000–1100 °C) (Cuomo di Caprio 2007, 38).[9] Production of better-quality steels also required closer temperature control, in both smelting and smithing. Concern as to the production of the 'right' quality of charcoal became more necessary, as well as provision of sufficient woodland to provide the charcoal. Production of glass reached very sophisticated standards (see Cool, this volume). In all of this consumption, however, except for some localized examples, the Romans did not seem to deforest their empire. A pattern of conservative management of woodlands related to fuel or timber use in peninsular Italy appears to have occurred, despite clearance for agriculture. It is fair to say, though, that we do not have all the data to be entirely sure of this fact yet, and patterns in the provinces vary. Islands were more vulnerable. On the island of Elba, where iron ore was found in such abundance, ore was shipped to the mainland for processing by about the third century BC, as apparently the wood had run out for smelting and working the ore into bars for export elsewhere (Costantini et al. 2013). The Romans appear to have exploited (at times unreasonably) some provincial forests more than those of peninsular Italy. However, even here, climate and soils may have been larger factors in forest cover changes (e.g. in North Africa). These matters are ongoing (and long-term) subjects of investigation. Large-scale deforestation does not show up in the European pollen record until the medieval period (see especially Harris 2011, 2013, 2017). For Italy, a recent summation of a large database of archaeobotanical records for the Holocene (Mercuri et al. 2015) suggests irreversible land transformations commenced (in terms of tree composition) from the middle Bronze Age, but not necessarily large-scale deforestation. One aspect that has been little studied is carrying capacity. Although Roman fuel consumption was relatively high (cf. other ancient societies), it was probably not high enough to deforest the empire, if total carrying capacity is considered (vs the population). Carrying capacity estimates need to be carried out in conjunction with reconstructing landscape use in more detail (and reconstructing population ranges). There is much work to do.

Roman fuel consuming activities: wood or charcoal?

Turning to Roman fuel consuming activities, we need to consider which ones used raw wood, and which charcoal. Clearly those that required the use of charcoal were ultimately consuming more forest than those that required raw wood. We know from the historical sources, for example, that braziers used charcoal,[10] and that both charcoal and wood were called for in the kitchen. We don't know in what proportion. Figure 1.3 provides a diagram of the various fuel-consuming processes and their probable fuel type(s).

In some cases we cannot know for sure whether charcoal or wood was used (but see the discussion on 'reflectance' below). From Figure 1.3, it may be inferred that in general, the hotter and more constant the temperature required, the more probable it is charcoal will have been employed. However, this is not the only consideration. Modern analogies suggest the Pareto (80/20) rule could have applied – that in cities, 80 per cent of fuel was charcoal and 20 per cent was wood (with the reverse ratio in the country).[11] This is understandable with charcoal's more constant burning qualities, and the fact that it burns with little, or no, smoke. Further, it is one-third the weight of raw wood (by volume), and as we have already seen, nearly double the calorific potential. Temperature processes requiring a temperature of 1100 °C appear to need charcoal. Very little archaeological evidence is available for glass-making. We must also differentiate between wholesale raw glass production and glass-working (less heat is required for glass-working, as the already chemically created material only needs to become plastic for working; see Cool, this volume). Few sites have been discovered in the Roman Empire for the former, whilst indirect evidence for the latter is more common. In the case of iron smelting, charcoal is not only required for temperature but also is an intrinsic part of the chemical process. Archaeometallurgists commonly remark that they would also expect charcoal to be used for easier fire control (and in chemical

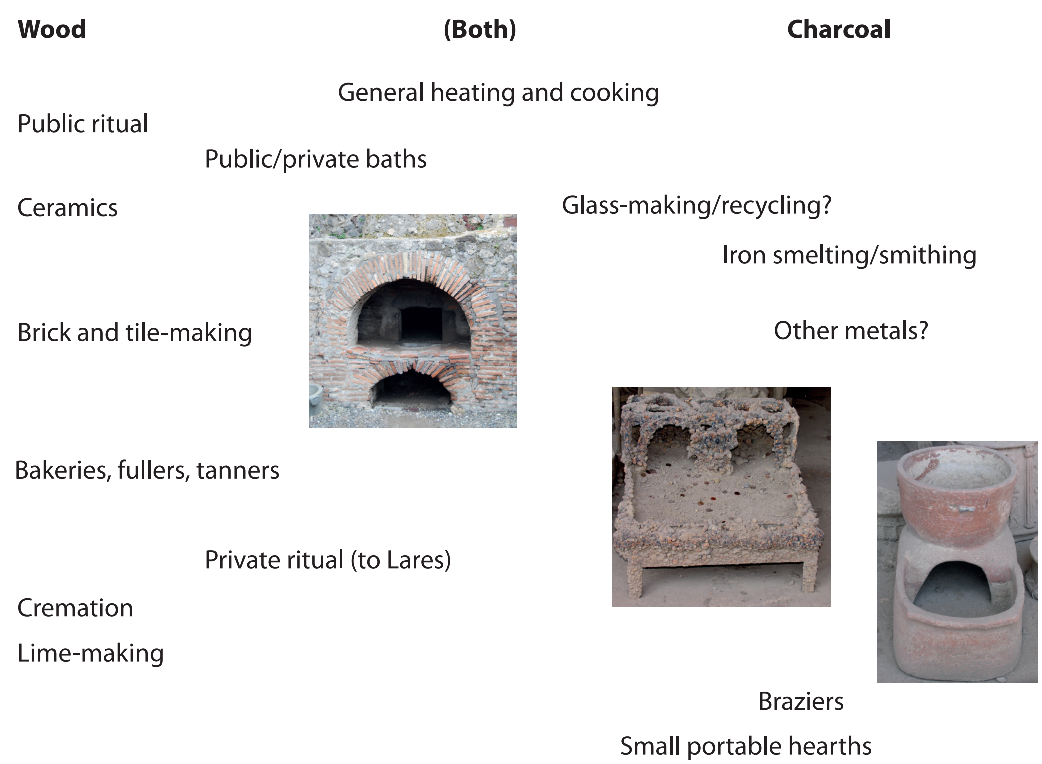

Figure 1.3. *Probable fuel types for different activities (figure and photos by Veal).*

reduction as well) for lower melting/smelting point metals; however, we do not yet have proof. It is also possible that other fuels were used, and even more probable the further back in time we proceed.

Moderators of fuel consumption

It is logical that fuel consumption went up with: cooler or wetter (micro-) climate; the predominance of cremation in burial practices; technological advancements (requiring higher temperatures); increased population (increasing domestic and industrial demand); increased urbanization (increasing charcoal consumption); increased wealth (promoting perhaps more profligate use of fuel); and in times of war (when demand is also heavier, not only on the fuel supply for manufacture of weapons, but also for cooking and heating for troops).

Other activities relating to particular social mores that can increase fuel consumption which have not yet been examined in any detail include elaborate funereal feasts; regular re-visitations and celebrations at tombs (both of which are essentially private activities); and elaborate public feast days (state or emperor funded). See, for example, Small (2018) and Veal (2017b).

Pricing and transport

Cities, in particular large cities like Rome, probably consumed much more charcoal than wood, and had a significant supply system in place. We know from the historical sources, toponyms and logistical analyses that timber for Rome was supplied from as far away as modern-day Umbria.[12] Transport of the lighter charcoal may have been cheaper, but would cause more damage to the charcoal (resulting in 'fines' that may not be useful industrially, but are still useful domestically for one purpose or another.) There is little pricing information in the historical sources, except for Diocletian's Edict (Graser 1959). Notwithstanding the recognized issues with this source, Diocletian shows us that *ligna* (fuel) is clearly differentiated from *materia* (timber). For fuel, kindling was highly prized, and charcoal was more expensive than raw wood fuel, although this can only be discerned from the transport prices of these products (and as in the modern world, transport appears to make up a significant portion of the cost). Non-wood fuels are not mentioned in the Edict.

Modelling the size of the wood fuel supply

Various approaches to modelling all Roman energy consumption have been made. Those focusing on fuel alone are currently few in number. A useful review for the Roman period is provided by Malanima (2013). Normally his time period of focus is post Roman to early modern, and so he perhaps underestimates Roman wood fuel consumption, not allowing for the excesses of public bathing and feasting, among other issues; however, the range of his work is highly instructive. For the upper Rhine region, another broad model based more on landscape, archaeobotanical and historical data, examines supplying the Roman Army (van Dinter et al. 2013). This has the advantage of consideration of cultural inputs, but the fuel supply calculations are broad brush (and explicitly exclude bath supply).

A model to calculate the amount of fuel a city might use in a year has been proposed by this author. Initial efforts focused on an individual house (the House of the Vestals) and then Pompeii as a whole.[13] The approach was recently modified for Rome (Veal 2017). Simply put, the estimated population of the city is firstly multiplied by the volume of wood per head consumed (ranges are estimated based on ethnographic data and ancient socio-economic considerations). An adjustment has to be made to account for the amount of wood used in charcoal-making, and then the total is divided by an estimate of forest productivity (again, allowance is made for a range of productivities). Together these provide an estimate for the area needed to grow the wood fuel. Examining the volumes of wood required, and taking into consideration the ecological constraints suggested by the actual wood types identified in archaeological charcoal, we may start to make more informed inferences about possible growth areas. Competition with other agricultural activities must be considered. This model still lacks refinements to include 'quality' of charcoal (i.e. how much was 'industrial' in nature, or 'domestic'). It is currently a linear model using a range for each of the variables, which may be applied to other cities where some notion of population and forest productivity ranges may be gleaned from ecological and ancient sources. A refined version employing a Bayesian probabilistic approach that tests the sensitivities of the various variables is under preparation.

Another recently published model (Janssen et al. 2017) also attempts to calculate the fuel consumed within one town. It makes for useful reading in conjunction with the chapters herein, as it focuses specifically on wood consumption in the Roman Baths and for red-slip ware production (but only for these activities). The site is Sagalassos during the second century AD. A Monte Carlo approach is used to account for uncertainties in the variables discussed, and many of the assumptions and ranges of variables seem very appropriate. However, by focusing on bathing and ceramics, the study can omit considerations of the increased wood required from charcoal consumption since, as the authors argue, these were activities that probably only used raw wood. Their subsequent, although brief inclusion of archaeological charcoal analysis results, and ecological assessment, provide an integrated approach. They conclude that the area required for wood production was high, and close to the maximum space available (for these two activities alone). Pollen records however, do not show large-scale vegetative change. Questions therefore arise about the possibility of the use of non-wood fuels on a significant scale, and/or wood importation perhaps from a nearby region (as is proposed for Pompeii). Finally, we do not yet have enough information to assess the relative size of the consumption of fuel from these two industrial activities, in comparison with every other use of fuel at Sagalassos.

All of these recent attempts to model fuel consumption provide useful input towards progressing our understanding of local and city-wide consumption. They approach the matter more from a 'bottom-up' strategy, and most require refinement to include greater accuracy of variables, in particular, as well as the relative volumes of consumption by different technologies, and the use of charcoal vs raw wood. Adding in 'domestic' consumption is another challenge, and here again we require better refinement of population data than currently is available for most cities.

History of wood charcoal analysis

Charcoal collection and analysis has been well described in a number of publications,[14] and has been undertaken to some degree or other since the 1940s. Results have mostly been framed in terms of wood lists, and an emphasis on a presumed fuel collection strategy of 'Least Effort' coupled with subsequent inferences about how the proportions of wood identified might relate to the potential environment (Chabal 1992; Shackleton & Prins 1992). An inherent assumption is that 'selection' does not play a big part in the wood fuel collection process. This may be true for prehistoric periods to a large extent (but see Picornell Gelabart et al. (2011)). Work in historical periods suggests city fuel provision had to be more strategic and managed. Increased urbanization (a feature of the Roman period) dictated the necessary cultivation of fresh and perishable goods closer to cities (dairy, most fruits and vegetables, flowers), with less perishable goods being cultivated at further distances. Hence in large (and even smaller) Roman towns we might expect to see evidence of a managed fuel economy. In smaller, rural areas, local supply of available materials might be expected. Even for the city of Rome at its height, however, there is little epigraphic evidence for mass movement of wood fuel across the Mediterranean (and no archaeological evidence to date). Woods may well have travelled intra-regionally, probably by cabotage, by river, or short distances by road. Exotic woods, when detected archaeologically in low forested areas (e.g Roman North Africa and Egypt), are thought to represent either construction waste (in very small quantities), or the burning of wooden tools/objects (van der Veen et al. 2011). Timber marketing and transport is a different issue, and Mediterranean movements are documented in literary and epigraphical sources, and archaeologically.

Besides identification, analysis has now moved forward to explore tree ring curves and counts for cropping marks. See, for example, Marguerie (2011), and references therein. Charcoals recovered in dry sieving in excavation, and in the laboratory, are subject to continual breakage; however, this does not seem overall to bias results too much, providing that over-examination of small (<4 mm) fractions does not occur (Chrzavzez et al. 2014; Chrzavzez et al. 2011). Charcoal collected from flotation fragments a lot and then often requires subsampling at the microscope. More problematic is the issue that charcoal may only be collected opportunistically (e.g. when sighted), or by targeted analyses (i.e. from hearths or ovens). Systemized random sampling, as well as targeted analyses, are both useful strategies, but consistent collection, through time and space, is the only way to produce representative results. Charcoal is usually ubiquitous in urban environments, but collecting it only from hearths or ovens means sampling of just the last, or last few, burn events. These will be primary, or near primary contexts (which are intuitively preferred by archaeologists and historians). However, to gain a view of the wood fuel supply (or indeed the food supply) over time, collection of material from all types of contexts, including general secondary and refuse deposits is essential (as is preferred by bioarchaeologists and statisticians).

The reflectance technique: differentiating raw wood and charcoal fuel

We also require much more information as to the proportional use of charcoal vs raw wood. This is a key issue (as is the part non-wood fuels may have played). The reflectance technique is a laboratory procedure borrowed from coal assaying, that relates the 'shininess' (i.e. reflectance) of charcoal to its absolute burn temperature (i.e. the highest temperature to which the charcoal has been exposed). Experimental work on modern charcoals, and the subsequent creation of calibration curves to relate measured reflectance to temperature, have been completed in the last few years, although for the most part not by archaeologists. See, for example, McParland et al. (2009a). Braadbaart and his colleagues have carried out considerable experimental work in the laboratory in this area (and some limited work on archaeological charcoals) (Braadbaart et al. 2016; Braadbaart & Poole 2008; Braadbaart et al. 2012; Braadbaart et al. 2009). This experimental work is valuable, but we need to extend our examination of archaeological material, and verify that the measures he suggests will aid archaeological interpretation.[15] Some work on archaeological charcoals has produced mixed results to date (McParland et al. 2010; McParland et al. 2009b; Veal et al. 2016).[16]

Conclusion

This discussion has offered a broad insight into the complexities of the Roman fuel economy, exploring some of the major uses of fuel, and aspects of the science behind charcoal manufacturing and consumption. The chapters that follow examine aspects of particular uses of fuel, using a range of data from ancient historical sources, archaeological and archaeobotanical evidence, ethnographic parallels, and some quantitative modelling. They focus mostly on kiln technologies, as well as some exploration of non-wood fuels. Ultimately, we would like to be able to rank, according to demand, all of the Roman activities that consumed fuel, coupled with chronological and geographical patterns. Modern analogues suggest domestic use outweighed or equalled industrial demand (but we must be careful not to be too free with projecting developing world parallels back into the ancient period). There is much work to do. We are just beginning to unravel fuel in the ancient Roman world, and indeed the ancient world in general.

Notes

1 Thommen's 2012 work is well regarded by ancient historians, but less so by some archaeologists and scientists. He fails to integrate these areas well enough in his analysis. Hughes wrote in 1994 of Pan's Travail, and we could possibly forgive the lack of scientific and archaeological integration at that time. However, he further defended his position of the Romans being great deforesters in 2011, with a very limited examination of three small case studies (referencing pollen, charcoal and modelling). This restatement showed little understanding of the limits of either palynological or charcoal examination. He refers to models that simplistically incorporate historical data at face value. He does not define 'deforestation', including all sorts of forest and agricultural cover changes (whereas deforestation is usually defined as permanent removal of any and all trees). He fails to account (even in 2011) for any contribution from soils or climate; or the continuity of change through time of nearly all of the landscape (well before the Romans). Despite writing this 'update' in 2011, the small case studies examined (and most of his references) are from the 1990s. Work has progressed since then. See especially Harris (2013).

2 The author's early work in this area, and some subsequent laboratory studies currently in publication, were carried out in the Department of Archaeology, University of Sydney. Some of the ideas expressed in this chapter were presented at a conference in Rome, 'History and Environment in the Ancient Mediterranean', held at the American Academy in Rome and the *Institutum Romanum Finlandiae*, 15–16 June 2011, and hosted by Prof William Harris, and subsequently appeared in Veal (2013). The idea for the conference owes its gestation to those discussions and the ongoing encouragement of Prof Harris, and I thank him for his generosity of time and intellect. I also thank all of the directors of excavations who have invited me to examine their charcoal.

3 A small quantitative model, developed for evaluating the fuel economy of Pompeii, may be found at https://www.robynveal.com/a-quantitative-model-for-the-ancient-fuel-supply-to-pompeii-ad-79.html

4 We can't precisely tell while excavating whether charcoal remains originated from raw wood or charcoal fuel, but a test to assist us to determine this called 'Reflectance' is being trialled. See, for example, McParland et al. (2009a); see also notes 15 and 16, below. Modern data also clearly distinguishes between 'domestic' and 'industrial' charcoals and their differing qualities (see http://www.fao/docrep/x5328e/x5238e0b.htm; however, this is still developing in archaeological research.

5 Found online at the Lacus Curtius site. Bill Thayer curates these pages made up of primary (and secondary) historical sources that are out of copyright. The extended and revised commentaries of Thayer significantly augment older Loeb translations.

6 Denser, harder woods tend to make better-quality charcoal for metal smelting and smithing.

7 http://www.fao.org/docrep/x5328e/x5328e0b.htm, section 10.1.5, provides details of some comparisons between various wood charcoals and other organics.

8 http://www.fao.org/3/ab780e/ab780e04.htm tells us that ovens in developing countries are usually below 50 per cent heat efficiency for a variety of reasons.

9 Cuomo di Caprio (2007) provides a detailed elucidation of firing modalities for all types of ceramics.

10 According to Columella, Pliny the Elder and Apicius (Meiggs 1982, 264–70). Meiggs is still the best collation of the ancient sources.

11 Otherwise known as the 80/20 rule. Vilfredo Pareto observed that this ratio applied to many economic, financial and natural phenomena. In the case of wood and charcoal it is proposed that the richer citydwellers used 80 per cent charcoal (a more expensive commodity) and 20 per cent wood, while the poorer country-dwellers

used the opposite quantities of each. Much more research is required to examine this question.

12 For detailed analyses see, for example, Diosono 2008a; Diosono 2008b; also Veal (2017c).

13 http://www.robynveal.com/a-quantitative-model-for-the-ancient-fuel-supply-to-pompeii-ad-79.html

14 Leney & Casteel (1975). See also Asouti (2007 and onwards) and Veal (2012b).

15 McParland et al. (2009b) review the previous literature in detail. This work is still in its infancy as researchers have developed calibration curves that can differ by around 150 °C for any one reflectance temperature. Cooperation between laboratories to resolve this issue is required.

16 Neither of these studies prove the method is yet successful for *accurately* measuring, e.g., the burn temperature of a particular process (in these cases, a hypocaust and Bronze Age cremations). Resolution of the calibration issue is required. In a further study yet to be published, more encouraging results for charcoal obtained from iron slag have been obtained by the author. The method does, however, appear very suitable for discerning charcoal fuel from raw wood fuel and testing is continuing at a number of laboratories.

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Fuel and Fire in the Ancient Roman World

The study of fuel economics in the Roman, or indeed in any ancient world, is at a pivotal point. New research in archaeological science, the ancient economy, the ancient environment, and especially, the increasing collection of bio-archaeological datasets, are together providing a greatly enriched resource for scholars. This volume makes a first attempt to bridge the gap between 'top-down' generalized models about Roman energy consumption with the 'case study' detail of archaeological data in the Mediterranean. The papers here are the work of scholars from a variety of disciplines: from archaeobotanists and historians to archaeologists specialising in social, technical and economic fields. A more nuanced view of the organization of the social and industrial structures that underpinned the fuel economy arises. Although focused on the Roman period, some papers extend beyond this era, providing contextual relevance from the proto-historic period onwards. Much exciting interdisciplinary work is ahead of us, if we are to situate fuel economics more clearly and prominently within our understanding of Roman economics, and indeed the ancient Mediterranean economy.

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