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Fuel for debating ancient economies. Calculating wood consumption at urban scale in Roman Imperial times

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ABSTRACT

Estimating wood extraction rates from forests based on archaeological and historical evidence is an important step in evaluating the sustainability of past social-ecological systems. In this paper, we present a calculation tool to estimate human wood resource use for a selected location during a defined period in the past. We illustrate the method by its application to the ancient town of Sagalassos (South-west Anatolia, Turkey) during the Roman Imperial period, with a focus on pottery production and the Roman Baths. Based on archaeological data, thermodynamic formulas and calorific values, an estimation is provided of the amount of wood used within a time step of one year. Because quantitative information on ancient technology and lifestyle is rather scarce and uncertain, input values consist of ranges. In order to take this uncertainty into account, a Monte Carlo procedure is included, offering a probability distribution of possible outcomes. Our results indicate that wood consumption in 2nd century Sagalassos was quite high, with a lifestyle including frequent hot bathing, export driven pottery production and a climate that required heating during winter months. Based on the available woodland area, we conclude that the community of Sagalassos was intensively using the surrounding forests.

1. Introduction

Wood was humanity's first source of energy. Up until the industrial revolution, it was by far the most important fuel for households and crafts and was an important material for construction (Malanima, 2013). Even today, wood remains the dominant energy source for cooking for almost 40% of the world's population, albeit mainly in developing regions (OECD/IEA, 2013). Unsustainable wood harvest can lead to forest degradation, deforestation, wood shortage and a loss of forest ecosystem services such as soil protection and water regulation.

The concept of sustainability originates from forestry and was introduced in 1713 by Hans Carl von Carlowitz in his essay *Sylvicultura oeconomica*, in which he proposed the principle that only as much wood as could be regrown should be harvested. Centuries later, the Brundtland Report (1987) defined sustainable development as '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*', a rather broad and vague definition. For forestry, this concept was translated into seven principles of sustainable forestry in the '*non-legally binding instrument on all types of forests*' adopted by the United Nations in 2007. These principles cover the economic, ecological and social functions of forests. In this paper, we will focus on the economic aspects of sustainability, and more specifically on the balance between wood harvest and regrowth. Estimating wood extraction rates based on archaeological evidence is clearly an important part of this analysis and is essential for evaluating the sustainability of past social-ecological systems.

Although interesting studies on energy consumption (Malanima, 2013) and deforestation (Hughes, 2011; Harris, 2013) in the Roman world do exist, they rely mainly on historical and palynological data. Kaplan et al. (2009) simulated spatial and temporal trends in anthropogenic deforestation in Europe and large parts of the Mediterranean based mainly on population density and the amount of arable land required to feed this population. However, their model fails to address deforestation caused by wood harvest, e.g. for metallurgy. Veal (2012) used ethnoarchaeological data to model the fuel consumption of Pompeii in 79 CE based on per capita wood consumption. While the method used in this study is very useful, it is difficult to take the effects of industry or public facilities in cities into account using this approach. In this paper, we present a novel calculation tool to estimate human wood consumption for a selected location during a defined period in the past. The calculations are based on archaeological data and account for the associated uncertainty of these datasets. We illustrate the method by applying it to the ancient town of Sagalassos (Southwestern Turkey) during the Roman Imperial period. We first present a conceptual overview of

Abbreviations: CV, (calorific value); SRSW, (Sagalassos red slip ware).

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our wood consumption tool and then go into more detail for the Roman Imperial Sagalassos case study.

2. The XylArch tool

2.1. Conceptual model

In order to investigate the impact of a community on the surrounding forests, we need information on both the harvest and production of wood. Wood harvest is defined as all the wood that is extracted from a certain area by humans, whether it is extracted for energy or non-energy purposes or exported to other areas. On the other hand, when wood is imported to a defined area, this is regarded as a reduction in the amount of wood harvested in that area. Wood production is defined as the amount of suitable wood that grows in a certain area. In a sustainable system, wood harvest is lower or equal to wood production within a certain area and time frame.

Wood harvest depends on the wood-based energy consumption, the amount of wood used for non-energy applications and the export and/or import of wood (Fig. 1). To estimate the amount of wood that is used for energy purposes, we first need to estimate the amount of wood-derived energy that is consumed by households (mainly for heating and cooking), public facilities (e.g. for the heating of public buildings, such as bath complexes) and craftsmanship (e.g. for pottery production, metallurgy). If we then know the energy content of the wood, we can derive the amount of wood that is needed for the estimated energy consumption.

A second important component of wood harvest is non-energy wood consumption, which can also be divided into the same major sectors: household construction and furnishing (e.g. wooden floors, doors and shutters), public facilities construction (e.g. roof construction) and handicrafts (e.g. carpentry tools).

Since the production of wood is typically expressed on an annual base, calculations of wood harvest are also done annually. This ensures that all calculations are intercomparable and that seasonal variations are included.

2.2. Energy use

2.2.1. Energy consumption

The energy consumption of past communities is calculated in separate modules for households, public facilities and craftsmanship. Since each society has its own unique characteristics, communities have their own sets of modules. This first version of the tool provides a calculation of the two main energy consumers of craftsmanship and the public sector of Sagalassos, respectively the local pottery production and the Roman Baths. The energy consumption of households is very complex

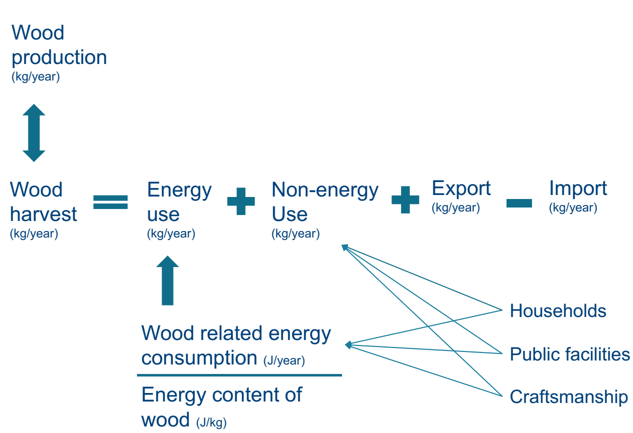

Fig. 1. Conceptual model of the XylArch tool. Only the 'Energy use' component is incorporated in the current version of the tool.

and, although research is ongoing, little information relevant for our purpose is currently available. For this reason, a detailed calculation on the wood consumption of households is not yet available, but an estimate of total wood consumption based on population size is given in the discussion part of this paper.

2.2.1.1. Pottery production. The amount of energy needed for pottery production can be calculated based on the amount of clay fired and the energy needed to fire this clay. The amount of fired clay can be estimated based on the number of kilns, their firing rate, the kiln load and the vessel weight (formula (1)). Please refer to Appendix A for further explanation of the variables.

$$Q = \text{kilns} \times \frac{\text{firings}}{\text{year} * \text{kiln}} \times \frac{\text{vessels}}{\text{firing}} \times \frac{\text{kg}_{\text{clay}}}{\text{vessel}} \times \frac{\text{Joule}}{\text{kg}_{\text{clay}}} \quad (1)$$

2.2.1.2. Roman bath complexes. The energy requirements of Roman bath complexes (i.e. the amount of energy needed to heat the rooms and bathwater) can be calculated based on thermodynamic formulas.

The amount of energy needed to heat the rooms or spaces can be roughly estimated using a general thermodynamic formula (formula (2)) that calculates the amount of heat that is lost through the floors, walls, ceilings and windows. Please refer to Appendix A for further explanation of the variables/parameters.

$$Q_{space} = \lambda \times A \times \frac{dT}{dl} \times t \quad (2)$$

The amount of energy needed to heat the water can also be calculated using a general thermodynamic formula (see Appendix A for further explanation):

$$Q_{water} = c \times m \times dT \times V \quad (3)$$

The total amount of energy needed for Roman bath complexes is the sum of the energy needed to heat the water and the rooms, divided by the percentage of energy that is not lost to the environment (efficiency of the system, see Appendix A for further explanation):

$$Q_{Roman\ baths} = (Q_{space} + Q_{water}) \times \frac{1}{Efficiency} \quad (4)$$

2.2.2. Energy content of wood

The energy available in wood is called the calorific value (CV) of wood, which is the amount of energy released during complete combustion of the wood. The CV is determined by the chemical composition of the wood and its moisture content. In our calculations, we will calculate the amount of oven dry wood (calculated with CV_0, i.e. CV of oven dry wood) needed yearly with the following formula:

$$Wood = Energy \times \frac{1}{CV_0} \quad (5)$$

Please refer to Appendix A for further explanation of the variables/parameters.

2.3. Non-energy use and export and import

Non-energy wood consumption is not discussed in this paper. Wood used in furniture, construction and tools, for example, lasted for many years and could often be recycled. We therefore consider its proportional consumption negligible to energy-related wood consumption, which consumed large amounts of firewood on a daily basis.

It is very difficult to archaeologically establish whether or not wood was imported or exported, let alone to calculate the amounts. The scale of import and/or export would have depended on the availability of wood resources after the basic needs of the society were met. Moreover, since wood transport is an energetically costly operation, import and export would have been limited to the more valuable types of wood and cases in which there was a particular need. Therefore, there is no calculation module for export/import available in the tool.

2.4. Dealing with uncertainty

A major problem that arises when trying to calculate past wood consumption is the lack of quantitative data. Most archaeological and historical data is qualitative or, at best, based on educated guesses. When quantitative data is available, earnest source criticism needs to be applied and the extrapolation of such data to other contexts should be questioned. This uncertainty in input data leads to uncertainty in output (Fig. 2). To account for this uncertainty, we assign a probability distribution to all input variables/parameters (see Appendix A for details). A Monte Carlo simulation is applied, resulting in a probability distribution of possible outcomes. Essentially, this simulation runs the calculations over and over again, each time using different input values taken randomly from the input probability distributions defined by the user. This results in a range of possible outcomes and the probabilities by which these occur. In this way, the tool provides a more comprehensive view of the results of the calculations.

2.5. Uncertainty/sensitivity analysis

We perform a combined uncertainty/sensitivity analysis on our calculations to evaluate the relative contribution of each input variable or parameter to the output uncertainty. We use the one-at-a-time method to perform this analysis, which is the simplest and most common approach. To use this method, we first set all input variables/parameters to fixed values (the mean value of our input range). We then vary each input variable/parameter over its entire value range, one by one, leaving all the other variables/parameters constant. We monitor the output and check which input variables/parameters lead to the highest variation in output. These are typically the variables or parameters for which our knowledge is limited and thus have a broad input range.

3. Xylarch: application to 2nd century CE Sagalassos

As far as can be established, the archaeological site of Sagalassos was first settled late in the 5th century BCE. The original small-scale community grew in importance and by 200 BCE started to invest in urban monuments, institutions and infrastructure. It also began to organize its territory, which would eventually grow into a 1200 km^2 dependency. Together with the towns of Selge and Termessos, Sagalassos is considered to have been one of the major Hellenistic towns in the ancient region of Pisidia (SW Turkey). By Roman Imperial times, Sagalassos claimed regional primacy and translated this in an elaborate urban building program, sustained by managing its territorial potential. The increasing urban activities are considered to have had a strong impact

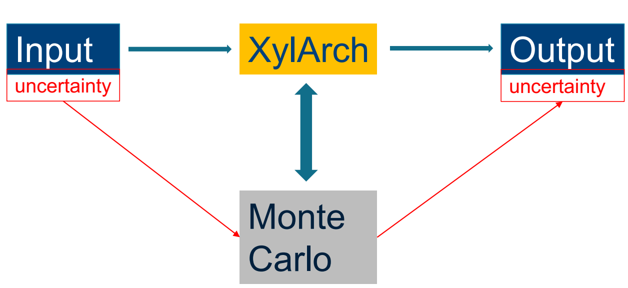

Fig. 2. Schematic overview of the XylArch tool dealing with uncertainty using Monte Carlo simulation.

on the surrounding forests through the harvesting of wood, land conversion and livestock grazing. While the forests were praised in ancient times, they were heavily degraded by the beginning of the 20th century (Planhol, 1958; Akkemik et al., 2012) and have only recovered over the last few decades.

The Roman Imperial period, and more precisely the 2nd century CE, is chosen as the research period for this study since it was a stable period for the region of Pisidia in general and a flourishing one for Sagalassos in particular, resulting in an archaeological record rich in documentation on the subject matter considered in this paper.

3.1. Sagalassos red slip ware

In 1987, the Roman Imperial potters' quarter was discovered in the Eastern Suburbium of Sagalassos (Mitchell and Waelkens, 1988), extending over 3.5–4 ha. In this quarter, tableware labeled Sagalassos red slip ware (SRSW) was produced in large quantities. SRSW consumption at Sagalassos (presumably mirroring production output) peeked in the 2nd and 5th–6th centuries CE and declined during the 3rd and 4th centuries (Fig. 3).

The study of the *chaîne opératoire* of SRSW has been one of the aims of the interdisciplinary archaeological program focused on Sagalassos (Poblome, 2013). The main stages of the production process were the quarrying and preparation of the clay raw materials, the provisioning of other required supplies such as water and fuel, the shaping of the vessels, their drying and slipping, and finally the firing of the products in simple updraft kilns (Poblome, 2016).

3.1.1. Estimating the amount of energy needed for SRSW production

For each term in formula (1), the values that were used as inputs for the XylArch tool are discussed below.

(1) number of kilns

Over the years, 19 kilns have been excavated in the potters' quarter of Sagalassos. However, only about 5% of the Eastern Suburbium has so far been excavated. These excavations are supported by geophysical surveying campaigns, which apply magnetic and ground penetrating radar methods and electromagnetic induction and have covered about 7.2 ha of the Eastern Suburbium (Mušič et al., 2008; Martens et al., 2012). Analysis of this geophysical data has uncovered a total of 135 detected kiln locations in the surveyed zone of the Eastern Suburbium (Claeys, 2016) (see Appendix B for details).

This represents the total number of registered kiln locations that would have sustained the entire SRSW production period between the end of the first century BCE and the second half of the sixth century CE in the Eastern Suburbium. However, these registered kiln locations were certainly not all used at the same time. On the other hand, many kilns may have remained undetected by the applied geophysical and archaeological strategies. The question thus remains, how many of the kilns were contemporaneous?

We use the diachronic consumption overview of SRSW (Fig. 3) constructed by Willet and Poblome (2015) to estimate the number of kilns active at the same time. This calculation results in an average of 79–87 kilns being simultaneously used during the 2nd century CE (see Appendix B for details of the calculations).

(2) $\frac{\text{firings}}{\text{year} * \text{kiln}}$

According to ethnographic evidence (Rye and Evans, 1976), firing takes place every 4–5 days in Pakistan, although this schedule is related to infrastructure, organization and the cultural/socio-economic context and thus may have been different in Roman Imperial Sagalassos (Murphy and Poblome, 2011). A typical working schedule may have been something like the following: one day to load the vessels in the

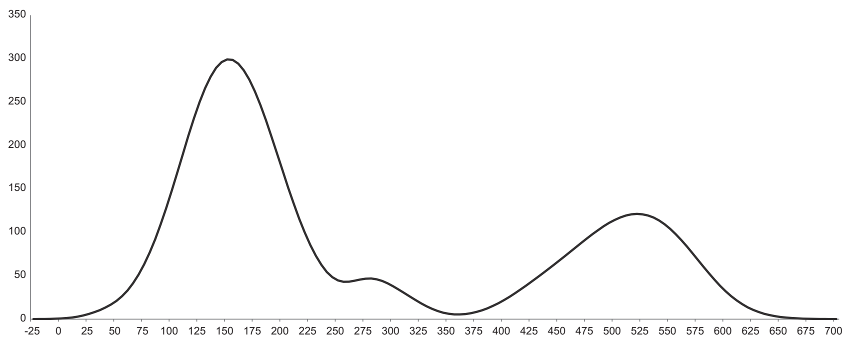

Fig. 3. Diachronic overview of SRSW using a Gaussian distribution method (n = 53.695 rimsherds) from a selection of representative and well-studied excavated contexts at Sagalassos. Calendar year (CE) is shown on the X-axis and number of rimsherds on the Y-axis. The decline during the 3rd and 4th centuries is probably exaggerated due to a lack of archaeological deposits available for this period. (Willet and Poblome, 2015).

kiln, two days to fire the kiln, one day to allow the kiln to cool down and another day to empty it. Weather affected the production process in a way that is difficult to estimate. During rainy days, it would have been impossible to fire the kiln. In addition, although the pottery was left to dry in an enclosed space, it was more difficult to dry the clay during cold days and there was a risk of the pottery cracking under large temperature differences between day and night. When there was a high demand for agricultural manpower, e.g. during the harvest season, it might have been necessary to shut down pottery production and allocate labor to the agricultural fields.

Since these influences are impossible to estimate and vary from year to year, we consider a minimum firing rate of once every 2 weeks over a five month period every year (resulting in 10 firings per year). The maximum firing rate is calculated as one firing every 5 days for eleven months a year (resulting in 66 firings per year).

$$(3)\ \frac{\text{vessels}}{\text{firing}}$$

Murphy and Poblome (in press) estimated the load capacity of a 2nd century CE kiln in Sagalassos at 1500–2000 vessels based on kiln size, the relative frequencies of the vessel types being loaded, the horizontal and vertical dimensions of those vessels and the methods of stacking each vessel type in the firing chamber. Kiln dimensions were measured at the excavated kilns at Sagalassos, while the vessel data was deducted from excavated and quantified contemporary dump deposits.

$$(4)\ \frac{\text{kg}_{\text{clay}}}{\text{vessel}}$$

The volume of clay for each vessel type used in the kiln load of Murphy and Poblome (in press), was estimated using a Matlab tool specifically designed for this purpose by Van Beeumen (2015). The calculations performed with this Matlab tool are based on the dimensions of the vessels and the profile drawings available in Poblome (1999). The average clay volume of a vessel was subsequently calculated based on the relative frequencies of the vessel types being loaded (Murphy and Poblome, in press). Since we know the density of the tableware (2.84 kg/dm^3 after firing; measurements by Patrick Degryse, taken into account a weight reduction of 8–12% due to firing (Rice, 1987)), we can also calculate the average weight of the vessels, which was found to be 0.24–0.82 kg.

$$(5)\ \frac{\text{Joule}}{\text{kg}_{\text{clay}}}$$

The energy consumption of a kiln depends on many factors such as the type of kiln, the capacity of the kiln and the firing temperature. The energy efficiency of many types of brick kilns is well known and ranges between 0.8 and 8 MJ/kg of clay (FAO, 1993; Van der Zwan, 1997; Maithel, 2003). The scotch brick kiln is an updraft kiln that most closely resembles the excavated examples of Roman pottery kilns at Sagalassos. The scotch brick kiln has an energy efficiency of 2–8 MJ/kg of clay (FAO, 1993); therefore an equal efficiency range is assumed for the updraft kilns of Sagalassos.

3.1.2. Estimating the amount of wood needed for SRSW production

We use formula (5) to convert the amount of energy needed annually to produce SRSW into an amount of wood. We assume a CV_0 of 18.5–19.8 MJ/kg_{wood}, covering both softwood and hardwood species.

3.2. The Roman Baths of Sagalassos

For the average citizen of a Roman Imperial town, a visit to the public baths was an essential part of daily life. When Sagalassos was granted the neokoros title in the beginning of the 2nd century, a title which denoted its role in organizing the Imperial cult in these parts of Pisidia, a new bath complex was conceived to host and impress the many visitors that came to Sagalassos during the associated annual festivals.

The Roman Imperial bathing complex was divided into three sequences (Fig. 4): a western (I), southern (II) and central (III) sequence. Each sequence contained a dressing room (*apodyterium*), a cold room (*frigidarium*) with a large cold water swimming pool (*piscine)* and several smaller pools (*alvei*), a warm room (*tepidarium*) possibly containing several *alvei* and a footbath (*pediluvium*) and finally a hot room (*caldarium*) containing several *alvei*. The complex also contained a *palaestra* (an outside exercise yard surrounded by porticoes), service spaces and a public toilet located in one of the vaulted spaces underneath the bathing areas. The baths were heated with a hypocaust system that is described in further detail in Appendix B.

3.2.1. Estimating the amount of energy needed for the Roman Baths of Sagalassos

3.2.1.1. Space heating. For each term in formula (2), the input values for the application of the XylArch tool to 2nd century CE Sagalassos are discussed below.

(1) Thermal conductivity λ

It is difficult to determine the thermal conductivity of the brick-built walls of the Roman Baths. These walls were faced on the inside with marble. A cavity was created between the marble and the bricks by means of metal hooks and perforated tiles. Warm air flowed from the hypocaust through this cavity. The outer walls were built against an outside layer of limestone and had several glass windows. The thermal conductivity of brickwork is 0.6–1.0 W/m $*$ K and for limestone is 1.3 W/m $*$ K (TheEngineeringToolbox, 2015; VirtualMaths, 2015).

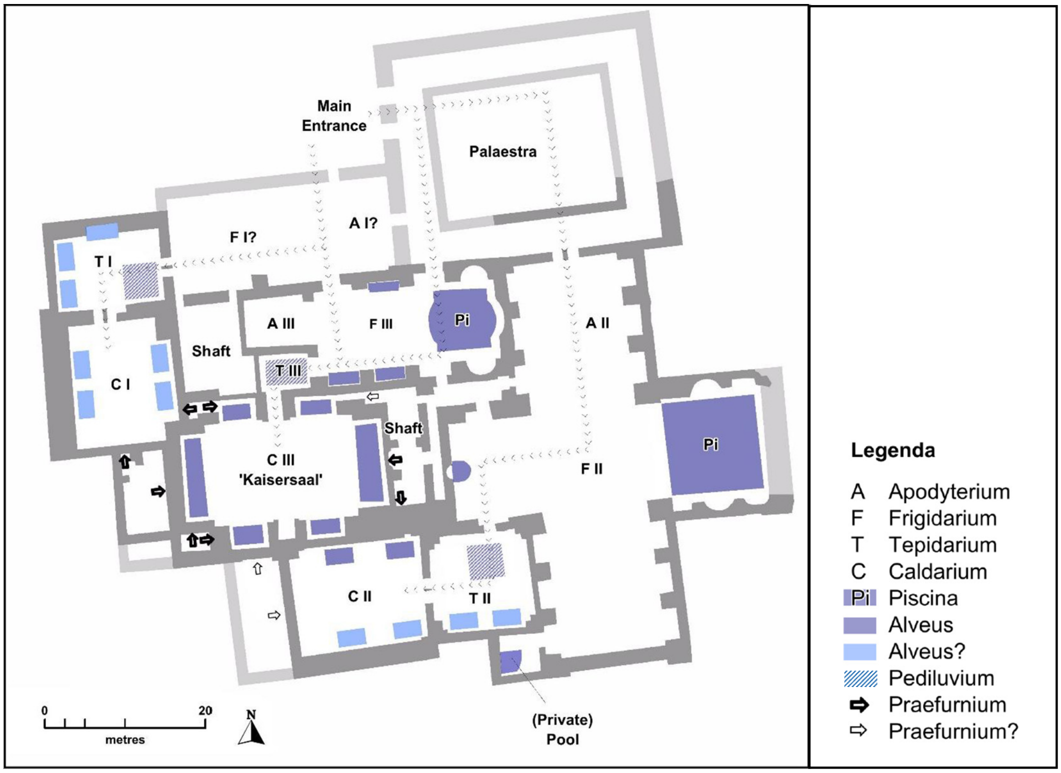

Fig. 4. The baths of Sagalassos.

Since the outer walls were a combination of brickwork and limestone, we assume an average thermal conductivity of 1.0–1.2 W/m*K. The ceiling is assumed to have been vaulted and consisted of mortared rubble on top of two layers of brickwork. Since concrete has a thermal conductivity of 0.4–0.7 W/m ∗ K (TheEngineeringToolbox, 2015; VirtualMaths, 2015), we assume an average thermal conductivity of 0.5–0.9 W/m ∗ K for the ceiling. For the glass windows, we use a thermal conductivity of 0.9–1.0 W/m ∗ K (TheEngineeringToolbox, 2015; VirtualMaths, 2015).

(2) Surface A

The surface over which heat is lost is calculated based on the architectural plan of the Roman Imperial baths of Sagalassos. The length of the outer walls of the heated areas was measured. Based on the preserved remains and the study of collapsed parts, the height of the walls is estimated to have been 5.5 m (see Appendix B).

Little information is available on the size and position of windows in the Roman Baths, so a range of possibilities is taken into account (see Appendix B).

(3) Thickness dl

The thickness of the walls was measured from the architectural plan. The typical window pane glass of Sagalassos measured 3–6 mm (Lauwers, 2008). The thickness of the roof is assumed to be 1.5 m (about 70 cm of mortared rubble and two layers of 40 cm bricks).

(4) Temperature difference *dT*

In this case, the temperature difference is the difference between the outside air temperature and the desired inside temperature in the different spaces. Local temperature measurements were derived from observations at the Ağlasun climate station (Kint et al., 2014) and corrected for the altitude of Sagalassos. This climate data is given in Appendix B.

Since traditional Turkish baths (hamam) are the direct and only descendant of Roman bathing technology and culture, and often employ a fully developed hypocaust system (Yegül, 1995), we assume that air temperatures in both are similar. Based on measurements in these modern baths and several theoretical calculations and reconstructions (see Appendix B), we assume a temperature of 23–30 °C in the *tepidaria* and 32–40 °C in the *caldaria*.

(5) Time over which warmth is lost

Rook (2005) heated a replica of the bath complex of Xanten (Germany) and found that it took 5 full days before the desired temperature was reached in the *caldarium* and its *alveus*. Kretzschmer (1953) heated a 20 m^2 room using a tubulated hypocaust system and it took 24 h to reach a room temperature of 20 °C. This indicates that the *praefurnia* must have been kept running 24/7 and were not allowed to cool down during the night.

Considering the harsh local winter conditions, it is unknown whether all three sequences were open year-round. Since bathing was such an essential part of daily life and deeply rooted in the Roman culture, we assume that at least one section of the bathhouse was open year-round. Since we have no direct evidence, we will consider different scenarios in which one, two or three sequences were open in the different seasons. See Appendix B for more details.

3.2.1.2. Water heating. Formula (3) is used to calculate the amount of energy needed to heat the water.

(1) Temperature difference *dT*

The temperature difference term in Eq. (3) refers to the difference in temperature between the mountain spring water entering the boilers and the hot water exiting. The temperature of the mountain spring water entering Sagalassos was measured during the summer of 2015 at the Hellenistic Fountain House and the Antonine Nymphaeum. At the Hellenistic Fountain House temperatures of 10 °C up to 17 °C were measured during the day, while at the Antonine Nymphaeum temperatures of 16 to 21 °C were measured.

In the modern day Turkish İnçirli hamam Brödner (1983) found that the water entering the caldarium measured 48 °C, while the baths had a temperature of 40 °C. Rook (2005) also measured a temperature of about 40 °C in the *alveus* of the *caldarium* in the replica of the bath complex of Xanten. In this replica, water was kept boiling in a lead boiler placed on top of the furnace. This water was mixed with cold water until the desired temperature was reached. We therefore consider the water exiting the boiler to be at a temperature of 100 °C.

(2) Volume to be heated V

The volume of water to be heated is estimated based on the volumes of the heated *alvei*, which are themselves estimated based on the architectural plan of the Roman Baths of Sagalassos (Appendix B).

These estimates represent the total heated water volume present in the different pools. In order to know how much water was heated each day by the boilers, we need to know the turnover time of the pools (the time it takes to refresh all the pools' water). Based on the turnover time of modern pools and a calculation of the turnover time necessary to keep the water temperature steady (Appendix B), we consider a turnover time of 6–28 h.

Finally, we convert the volume of water that is needed at 48 °C to a volume of boiling water (that is then mixed with cold spring water until it reaches 48 °C) (Appendix B).

3.2.1.3. Efficiency of the heating system. There is no data on the efficiency of Roman bath complexes. There is, however, some information on the efficiency of traditional cooking stoves based on the standard water boiling test (Bhattacharya et al., 2002). Bhattacharya et al. (2002) report efficiencies of 5% for an open fire, 10% for a traditional wood stove and 13–40% for an improved stove. The hypocaust system was highly efficient for two main reasons: (1) the heat (in the form of hot flues) that is not used to heat the water is channeled through the underfloor and walls in order to heat the rooms before it leaves the building and (2) it is a continuous large scale system. We could thus imagine a scenario in which 20% of the heat is used to heat the water and another 30% is used for the underfloor and wall heating, while 50% of the heat is lost. Given the uncertainty of these numbers, we propose a broad range of 30–70% for the efficiency of the heating system. See Appendix B for more information on the hypocaust heating system.

3.2.2. Estimating the amount of wood needed for the roman baths

In accordance with the calculations for the pottery production, we again assume a CV_0 of 18.5–19.8 MJ/kg_{wood}.

Table 1
Results of XylArch for 2nd century CE SRSW production. Outputs show mean and standard deviation for energy and oven dry wood consumption. The uncertainty/sensitivity analysis gives the percentage of variation in output that is caused by the respective input variable/parameter.

SRSW		
Output	Energy	14,600 ± 5500 GJ/year
	Wood consumption	760 ± 290 ton/year
Sensitivity analysis	Firing rate	35%
	Kiln energy demand	29%
	Vessel weight	26%
	Kiln load	7%
	N° of kilns	2%
	CV_0	1%

4. Results

The results of XylArch applied to 2nd century CE Sagalassos are given in Tables 1 and 2.

5. Discussion

5.1. Are our results reasonable?

In our most energy-saving scenario (2), 1670 tons of wood are burned each year for the baths of Sagalassos (this equals to about 4.6 tons/day and 191 kg/h). In contrast, when all three sequences are considered to have been open year round (scenario 1), almost twice this amount is burned. Our calculations show that a smaller amount of wood would have been required for the production of SRSW at 760 tons of wood per year (2 tons/day or 90 kg/h).

We can compare these numbers with data from reconstruction experiments, which give ranges from 1 to 7 kg/h for small baths (see Appendix D). Given the size of the baths of Sagalassos, with three sequences and up to 14 heated pools, our results seem high but reasonable.

For pottery production, there is, to our knowledge, no other data to support our findings. Given the high level of care and detail we have used to make the calculations, we think that our data will be useful for benchmarking other studies in the future.

5.2. Total wood consumption

As explained in Fig. 1, many activities affect the wood harvest. In Sagalassos, these activities include those related to households (heating, cooking, bathing, washing clothes, cremation, etc.), public facilities (heating buildings, baths, etc.) and craftmanship (production of pottery, brick and tile, glass, metal, lime, bread baking, etc.), as well as import and export. We have chosen to go into detail for two of the most well-

Table 2
Results of XylArch for operating the 2nd century CE baths of Sagalassos. Outputs show mean and standard deviation for energy and oven dry wood consumption. The uncertainty/sensitivity analysis gives the percentage of variation in output that is caused by the respective input variable/parameter.

Roman Baths		
Scenario 1: 3 sequences open year-round		
Output	Energy	59,400 ± 13,900 GJ/year
	Wood consumption	3100 ± 730 ton/year
Sensitivity analysis[a]	Window surface	26%
	Efficiency	23%
	Turnover time	17%
	Window thickness	14%
	Temperature in the caldaria and tepidaria	5%
	Outside temperature	4%
	Temperature of the mountain spring water	4%
	Volume of the baths	3%
	CV_0	2%
	λ (wall/glass/roof)	2%
Scenario 2: sequence II opened for 12 months, sequence I and III only during festival season (5 months, more or less overlapping with the summer season)		
Output	Energy	32,000 ± 7600 GJ/year
	Wood consumption	1670 ± 400 ton/year
Scenario 3: sequence II opened for 12 months, sequence I and III closed during the 4 coldest months		
Output	Energy	42,900 ± 10,100 GJ/year
	Wood consumption	2240 ± 530 ton/year

[a] The uncertainty/sensitivity analysis was performed for scenario 1 because it has the greatest variability in bath volume.

known and important processes: the production of SRSW and the operation of the Roman Baths. Although an in depth analysis of a few components is certainly useful and necessary to gain insight into the underlying factors that influence the wood demand, it was thus far not possible to do this for all aspects of Roman life. Little is known about many of these processes (e.g. the production of bricks and tiles in the territory of Sagalassos), and thus in-depth calculations on these topics would necessarily be rather hypothetical.

We can, however, compare our results with more general estimations of wood consumption found in literature. Since the energy system did not change much between the 5th millennium BCE and the 19th century CE (Malanima, 2011), we can even compare our numbers with more recent energy estimates. According to Malanima (2013), firewood consumption depends mainly on the mean annual temperature of a region and its industrial demand. Malanima (2006), Warde (2006) and Harris (2011) report pre-industrial firewood consumptions of 1 kg per person per day in the Mediterranean, about 4 kg per person per day in regions like Northern Germany, the Netherlands and Britain and up to 10 kg per person per day in northern Europe. Tolunay et al. (2010) report a consumption of 15 ton per household per year (8 kg per person per day) in the 1980s for cooking, house heating and water heating in a village close to Sagalassos (although gas and electricity was also available). Given its location in the mountains, the temperature of Sagalassos is more similar to that of northern Europe than the Mediterranean (see also table 1 Appendix B). Therefore, we consider a total consumption of 4–10 kg per person per day. Given that Sagalassos had an important pottery production center that was aimed at export (Willet and Poblome, 2015) and a bathing complex able to accommodate throngs of festival visitors, we expect a consumption closer to 10 kg per person per day rather than 4 kg.

The number of inhabitants in 2nd century CE Sagalassos is estimated to have been between 2500 and 3500 (Cleymans, in preparation) (see Appendix D for details). This leads to an estimated total wood consumption of 3650–12,775 tons per year within the city. According to Malanima (2013), in the energy system of the Roman world, firewood was used primarily for household consumption (mainly heating and cooking), with artisanal activities accounting for a smaller relative consumption. Our findings, however, are that at least 2430 tons of wood are needed each year to supply the baths and pottery production centers alone. This indicates that the energy demand of Sagalassos was quite high and possibly even exceeded 10 kg per person per day.

5.3. Fuel resources

In our calculations, we assume that firewood was the sole energy source even though other possible fuel resources, namely agricultural waste and dung, did exist at the time. However, the combustion of agricultural waste decreases the fodder supply, and the burning of dung leads to a decrease in the supply of organic fertilizer for arable land. Firewood is therefore the only energy source that does not conflict with fodder or fertilizer requirements (FAO, 1983).

When discussing wood fuel, we need to make a distinction between wood and charcoal. The process of making charcoal from wood was well known to the Romans (Veal, in press). Although charcoal is more expensive than raw wood, it has some important advantages: it is lighter, easier to store, has a higher energy density and produces less smoke. For iron smithing and smelting, charcoal is needed in order to reach and maintain the high temperatures required for this process. For other domestic and non-domestic purposes, we cannot be sure whether charcoal or wood was used. For purposes such as the production of pottery, bricks and tiles or the heating of the Roman baths, we can assume that wood was used because of the large amounts that would have been needed, the economic advantage of wood over charcoal and the space available in the kilns. Households probably preferred charcoal for heating and cooking if they could afford it (Veal, in press). The dimensions of a 6th century domestic cooking furnace found in Sagalassos (Poblome et al., 2015) indicate that charcoal, possibly combined with small wood, was used. In addition, braziers, although not found in Sagalassos so far, were commonly used for heating during Roman times and also used charcoal. To produce 1 kg of charcoal, 4 to 20 kg of wood are needed (Veal, in press). Since charcoal has an energy density which is almost twice that of wood (Veal, in press), the use of charcoal requires 2 to 10 times more wood to reach the same energy content compared to using wood directly.

Wood charcoal analyses on deposits of ash and charcoal remains (mainly domestic) in Sagalassos, provide us with information on the species used for burning. These types of deposits were selected as representative of the long-term firewood use at the site, since they are considered to be the result of multiple accumulation processes. In these analyses the relative frequencies of various species are calculated from the number of fragments of each species identified in the sample. These analyses indicate that the main species used for burning were cedar (*Cedrus libani* A Rich.), oak (*Quercus cerris* L.) and pine (*Pinus nigra* Arn. subsp. nigra var. *pallasiana*). Unfortunately, it is not possible to detect from these analyses whether the wood fuel was burned as wood or as charcoal. Please refer to Appendix D for a detailed description of the charcoal analysis.

5.4. Demand versus supply of wood within the territory of Sagalassos

Based on the tree species found in the charcoal analysis and the natural potential vegetation in the area (Kint et al., 2014), we can imagine a scenario in which wood is harvested mainly from cedar/pine forests and oak forests managed for pig herding (see Appendix D for further detail). Additionally, a smaller amount of wood was probably obtained from the management of the agricultural landscape.

We can roughly estimate the forested area needed to sustain Sagalassos by considering a scenario with a wood demand of 4–10 kg per person per day (see Section 5.2), a population level of 18,000–31,000 for the entire territory (Cleymans, in preparation) (see Appendix D for details), a density of 500 kg oven dry wood per cubic meter of fresh wood and an annual forest growth rate of 2–3 m^3/ha (OGM, 2014). This results in a required area of 18,000–113,000 ha of forested land to sustainably provide wood for Sagalassos (harvest = growth).

Based on extensive palynological data from the Gravgaz area near Sagalassos, we can estimate that 20% of the territory would have been forested during the 2nd century CE (Van Loo et al., 2016). Given that the territory of Sagalassos measured about 120,000 ha; approximately 24,000 ha of forested area would have been available.

It thus becomes clear that the community of Sagalassos was near the upper boundaries of sustainable use, and was possibly stressing its territorial wood production potential during the 2nd century CE. The palynological data, on the other hand, indicates that the forested area remained stable at around 20% until the 11th century CE (Van Loo et al., 2016), suggesting an intensive but non-depleting use over the longer term.

6. Conclusion

Based on archaeological data, thermodynamic formulas and calorific values, an estimation of the amount of wood needed for pottery production and to run the Roman Baths of 2nd century CE Sagalassos was made. The results of our analysis are reasonable and comparable to other archaeological and historical energy studies. Our calculation tool is easily applicable to other well investigated excavation sites and periods of interest, and its application to such scenarios could help to further validate and refine it. The next steps required for this research include a detailed calculation of other wood drains, such as the heating of private houses and construction work, and the incorporation of charcoal use into our tool.

Our results indicate that wood consumption in 2nd century Sagalassos was quite high, with a lifestyle including frequent hot bathing, export driven pottery production and a climate that required heating during winter months. Taking into account the forested area available within the territory of Sagalassos, we conclude that the community of Sagalassos was intensively using the surrounding forests. According to palynological data, a steady forested area was sustained, suggesting an intensive but non-depleting use.

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Supplementary data

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