IZA ROMANOWSKA, JOAN CAMPMANY JIMÉNEZ, OLYMPIA BOBOU, AND RUBINA RAJA*

Evaluating Environmental Kuznets Curves through Archaeological Data

A Conceptual and Theoretical Framework

ABSTRACT The Environmental Kuznets Curve (EKC) is a model of the relationship between environmental degradation and economic development. The model postulates that indicators of environmental degradation tend to be positively correlated with economic growth up to a transition point, after which the society starts deploying measures to reverse the environmental degradation leading to its decrease. This paper will introduce the EKC model and discuss the potential contributions archaeology can make to ongoing debates on the EKC. It will present several archaeological proxies that can be used, thus setting out a theoretical conceptual framework. The case study of Palmyra, a desert oasis city, and its hinterland will be used to demonstrate the potential and challenges involved. Establishing the validity of the EKC model is critical since it determines socio-economic policies. We argue that archaeological data has a strong potential to inform such debates.

KEYWORDS Environmental Kuznets Curve; environmental degradation; economic growth; urbanization; Palmyra

* Author contributions: all authors performed research, and wrote the paper. The authors declare no conflict of interest.

Acknowledgements and Funding Details

This research was undertaken within the framework of the project Circular Economy and Urban Sustainability in Antiquity: The Case of Palmyra directed by Rubina Raja since 2020. The project is co-funded by the Augustinus Foundation and the Carlsberg Foundation. Furthermore, funding was received from the Danish National Research Foundation for the Centre for Urban Network Evolutions (grant 119) for aspects of the work pertaining to the understanding of the urban development of Palmyra. Carlsberg Foundation, Augustinus Foundation, and Danish National Research Foundation funding was received by Rubina Raja. Iza Romanowska received funding through the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement no. 754513 and the Aarhus University Research Foundation. We would like to thank the two anonymous reviewers for their insightful and constructive comments.

Introduction

The Environmental Kuznets Curve (EKC) represents a model of a relationship between economic development, usually measured through income per capita, and environmental degradation, e.g. levels of various pollutants (Stern 2004). It is hypothesized that this relationship follows an inverse U-shape (Fig. 4.1). Initially, the economic growth increases the pressure on the environment leading to progressing degradation. This process is usually related to a shift from rural to more industrial-based economy, intensifi-

Iza Romanowska (iromanowska@aias.au.dk) is AIAS-COFUND Fellow at the Aarhus Institute of Advanced Studies, Aarhus University, Denmark. She works at the interface between archaeology and computer science using agent-based modelling and data science to study the past. ORCID iD: 0000-0002-9487-2111.

Joan Campmany Jiménez (joan.campmany@cas.au.dk) is a research assistant for the project Circular Economy and Urban Sustainability in Antiquity at the Centre for Urban Network Evolutions, Aarhus University, Denmark. He specializes in landscape archaeology and the archaeology of the Roman economy. ORCID iD: 0000-0001-8258-0528.

Olympia Bobou (olympia.bobou@cas.au.dk) is Assistant Professor in the project Circular Economy and Urban Sustainability in Antiquity at the Centre for Urban Network Evolutions, Aarhus University, Denmark. She specializes in classical archaeology, in particular classical sculpture and its social context. ORCID iD: 0000-0002-8995-3814.

Rubina Raja (rubina.raja@cas.au.dk) is Professor of Classical Archaeology at Aarhus University, Denmark, and Centre Director of the Centre for Urban Network Evolutions. She also directs the Palmyra Portrait Project and the project Circular Economy and Urban Sustainability in Antiquity. ORCID iD: 0000-0002-1387-874X.

Journal of Urban Archaeology, 4 (2021), pp. 61–97
BREPOLS PUBLISHERS
10.1484/J.JUA.5.126594

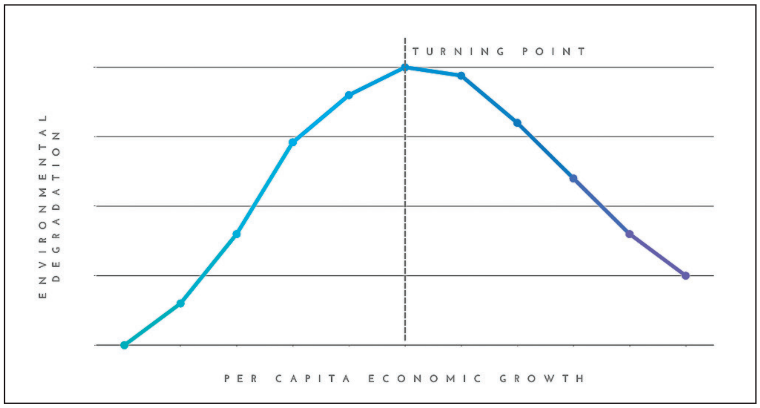

Figure 4.1. A depiction of a theoretical Environmental Kuznets Curve, showing the inflection point where economic growth translates into reduction of environmental degradation. In practice, the shape of curves derived from data is far less regular.

cation of production, and urbanization. In time, as the average wealth increases in the population, it is followed by improvement in terms of environmental impact. Several mechanisms behind this phenomenon have been proposed, such as raising awareness of the impact of pollutants on the environment and their repercussions on people's health, stronger regulatory drive by authorities, more income available for environmental protection, technological advances, or a shift towards the more service-based economy replacing traditional industry (Dinda 2005; Magnani 2000; Torras and Boyce 1998). Establishing the validity of the EKC model is critical since it determines whether to stymie economic growth for the sake of the environment or whether to promote growth in order to push developing countries beyond the threshold point.

The EKC model has raised substantial amounts of empirical and theoretical work due to its implications for public environmental policy especially in respect to developing countries and their economic trajectories. The idea that economic development could eventually lead to environmental recovery (often related to the concept of sustainable growth) has quickly gained popularity among policymakers and large international institutions, such as the World Bank (Stern 2004). Contrastingly, both the empirical and the theoretical foundations of the EKC model have received a fair amount of critique. For example, the model complies well with certain pollutants (e.g. lead) but not others (e.g. CO_2). In some cases, the decrease in environmental degradation is followed by another period of rapid increase in environmental degradation due to high levels of consumption (the so-called 'N-shaped curve') (Tsiantikoudis and others 2019). It is now very clear that while some environmental indicators comply well with the inverse U-shape, others do not, and that the model is more applicable to low- and middle-income countries than high-income countries and that in certain cases economic indicators other than income per capita display stronger correlations (Dinda 2004). While the debates on the validity of the EKC model are ongoing, researchers begin to find regularities regarding the particular circumstances under which the EKC model holds, e.g. it is more prevalent in urban contexts.

Establishing whether the EKC is an appropriate model for the relationship between economic development and environmental degradation is therefore of much interest. So far, the analyses have been based entirely on modern or relatively recent historical data. Here, we argue that archaeology, and in particular Roman archaeology, has good potential to provide high-quality comparative material with the benefit of a historical perspective. With more comprehensive temporal coverage in terms of long-term economic and environmental trajectories, archaeological datasets capture the full curve of a given economy, thus providing a new perspective and enabling more robust evaluation of long-term trends. Not only do we have a record of societies living in distinct environments and following diverse subsistence strategies, under different political and social organizations, and deploying diverse technological repertoire, we also know what has ultimately happened to them. Instead of trying to predict the environmental trajectories of developing countries — a potentially costly experiment — we could look in the past to determine the most likely outcomes under different circumstances and investigate which social, political, organizational, or economic factors have the most impact on sustainable balance between human groups and their surroundings. To achieve that, however, we need a robust framework grounded in data to enable us to evaluate the relationship between economic growth and environmental impact for archaeological case studies. This, in turn, would require a solid discussion about the proxies that could be derived from the record of past societies and methods that would enable us to overcome the known limitations of archaeological data such as its coarse granularity and, often difficult to quantify, uncertainties.

The objective of this review is to critically assess the feasibility of using archaeological data to contribute to the discussion on the relationship between economic growth and environmental degradation. Although plentiful, archaeological, historical, and palaeoenvironmental data presents a range of characteristics which means that the type of analysis undertaken on modern datasets is not possible. Given the lack of census data, such as the GDP and other economic indicators, and similarly limited access to time-series data that measure particulate pollutants in real time, the appropriateness of using proxies needs to be demonstrated. Ideally, multiple proxies of economic growth and environmental degradation should be collated and compared to evaluate their robustness and account for pre- and post-taphonomic biases (e.g. Banerjea and others 2017). In addition, given the coarse granularity of the archaeological record compounded with uncertainties inherent to the data, it is likely that several convincing case studies would have to be developed for a wider economic and social-science community to accept this kind of evidence.

The goal of this paper, thus, is to evaluate the potential of archaeological data to test whether the EKC model holds for past systems. We will briefly outline the current state of the debate regarding the EKC model focusing in particular on its weaknesses and known limitations. We will then review sources of evidence and possible proxies for the two factors in questions: per-capita economic growth and environmental degradation. Finally, we will use the ancient city of Palmyra as a case study to highlight the difficulties in acquiring the data, levels of uncertainty, and issues related to collecting representative datasets, and we will sketch out an agenda describing possible research lines that would enable this kind of investigation.

Environmental Kuznets Curves: The State of the Debate

Originally proposed by Simon Kuznets (1955), the inverse U-shaped curve referred to the relationship between economic growth (measured as income per capita) and economic inequality (measured as the Gini coefficient or the Kuznets ratio).[1] Using a set of indicators from several low-, middle-, and high-income countries he showed that although the initial phases of industrialization had led to increased inequality, in the later phases these differences had decreased. Important to note, this model demonstrated correlation between the factors, not implying a causal relationship. Since the original publication researchers proposed several potential causal mechanisms linking the two factors, such as universal education, democratization, the rise of the welfare state, urbanization, and a shift to a service-based economy. Similar to EKC, the Kuznets Curve model has been strongly critiqued and revised, especially as levels of inequality began to rise again since the 1980s. Kuznets himself noted the fragility of the model due to the limited time perspective and the particular historical context of the nineteenth and twentieth centuries of the datasets available to him.

The Environmental Kuznets Curve was a much later development first put forward in the early 1990s (Stern 2004). Despite gaining popularity among policymakers as a kind of middle way for developing countries where environmental protection and economic growth did not go hand in hand, the controversies related to data, its reliability as a proxy, and the timescale of analysis have been regularly voiced by researchers (Torras and Boyce 1998; Apergis and Ozturk 2015; Magnani 2000). The model has been tested on several case studies showing a range of contexts where relationships between environmental degradation and income per capita resemble an inverted U-shape. Among environmental indices that seem to comply with the model are sulphur dioxide, suspended particulate matters, carbon monoxide and nitrous oxides, industrial waste water, nitrogen oxide, lead, the DDT pesticide, chlorofluorocarbons, sewage, and deforestation (Dinda 2004). However, a wide range of pollutants do not seem to follow this relationship, most prominently among them the global levels of CO_2. It has also been shown that where certain environmental indices conform to the model in some groups of countries, they do not follow this relationship in high-income countries (Harbaugh, Levinson, and Wilson 2002).

On a higher level the main lines of criticism of the model focus on i) pollution export, ii) N-shaped curves, and iii) new toxins (Harbaugh, Levinson, and Wilson 2002; Stern 2004). First, it has been argued that rather than reducing the environmental impact, high-income countries simply 'export' the pollution, be it in the form of trash sent for processing abroad, relocation of production to other countries, or sourcing of products and services from parts of the world where environmental regulations are more lax. Second, the time perspective used in the analysis is of importance as in several cases the inverted U-shape changes to an N-shape as consumption rises (Tsiantikoudis and others 2019). Any gains in terms of limiting the environmental impact are lost due to the growing consumption that comes with higher income. Finally, in some cases a drop in the prevalence of a particular pollutant is caused by its replacement by another one often as a response to regulations. This creates an 'artificial' reduction, where in fact the environmental impact is the same or higher. The EKC models have also been criticized

1 For an introduction in relation to Roman archaeology, see Bowes 2021.

for using cross-sectional data (meaning data sampled at a particular time) and then inferring a temporal process by comparing different countries — each constituting a data point within its own trajectory. This, largely, is being rectified with a wider use of time-series data that follows each country/region throughout its historical records (e.g. Tsiantikoudis and others 2019), but it does highlight the importance of the time dimension.

It is clear that the EKC model applies to some environmental degradation indicators better than to others and that it works in some circumstances but not in all cases. The general characteristics of the types of environmental impact where, over a certain threshold, it negatively correlates with economic growth can be summarized as follows (Dinda 2004): i) they are related to health outcomes of the population (e.g. air quality), ii) the awareness of them is high (e.g. the DDT insecticide), and iii) they are easy to solve (e.g. lead). In addition, the model works more frequently in well-defined urban contexts where the density of the population exerts stronger political pressure on the policymakers to trigger regulatory mechanisms to reduce the environmental impact, especially when related to public health.

Finally, the use of income per capita as a proxy for economic growth has been questioned with researchers demonstrating that measures of equality are a better index. This indicates that the social and political context may be the true correlate rather than economy (Torras and Boyce 1998).

Archaeological Proxies

To test the validity of the Environmental Kuznets Curve model in an archaeological context, it is necessary to measure the two variables: economic growth and environmental degradation as well as independent factors that in some cases need to be controlled for, such as population size. Since for the vast majority of the past there has been no census data recorded, the challenge is to identify, quantify, and assess the uncertainty related to different archaeological proxies for those two aspects. The first variable, the per-capita income growth (also known as *intensive growth*, where per-capita output increases, to differentiate it from *extensive growth*, where the economy grows with population but per-capita output does not) may be measured through proxies related to the proportion of disposable income within a population or through the economic output. The second variable, environmental degradation, could in some cases be measured directly (e.g. level of pollutants in the soils) or extrapolated from the impact that the deterioration of environmental conditions may have on populations' size, health, and well-being. The spatio-temporal coherence is also required since each case study necessitates both the measure of economic growth and environmental degradation recorded for the same period and area and with similar spatio-temporal granularity. Importantly, since most of those measures are not independent from external factors such as climatic perturbations, historical events, or cultural and social transformations, these need to be controlled to contextualize the data patterns.

Economic Proxies

In recent decades, archaeologists have extensively debated which proxies can be used to measure economic growth in past societies (Bowman and Wilson 2009; Saller 2005; Scheidel 2009; Wilson 2009; 2014). This research trend comes after decades of traditional scepticism of classical archaeologists towards attempts at analysing ancient economies through the lens of modern economic frameworks. This concern has not been entirely put to rest as researchers continue to raise important issues with this approach. For example, Matthew S. Hobson (2014) argues that Roman economy studies have uncritically assumed the theoretical framework of development economics, which considers economic growth indispensable for welfare. In that framework, the Roman economy is to be considered either as an underdeveloped economy, or as an exceptionally developed pre-industrial economy. In both cases, a 'rational' organization of resources and productive forces is thought to underline economic growth, which in itself is seen as beneficial. Given that the last decades have been characterized by increasing inequality and declining living standards despite economic growth, the 'faith' in economic growth as a defining, or even a positive element in social change is being heavily questioned. Going further, Kim Bowes (2021) has recently pointed out how some of the latest attempts at grand discourses regarding the Roman economy have stretched limited datasets to the breaking point. Most of the focus is placed on Walter Scheidel and Steven J. Friesen's (2009) calculation of the Roman GDP, but her criticism can be extended to other scholars like Peter F. Bang (2008) and Peter Temin (2013; 2006) proposing particular models of economic framework. Instead, the author proposes a return to the household level, where more nuance and more reliable data can be found.

While the scepticism towards development economics and macroeconomic interpretations based on a small selection of limited datasets is valid, there are still reasons to measure economic performance in Antiquity, perhaps with several adjustments to the standard approach. First, archaeologists could use a wider range of metrics, more appropriate for the archaeological data. Koenraad S. Verboven (2018) proposes measuring proxies for the biological standard of living, for example reflected in the population's mean height, urbanization rates and city sizes, energy capture measured in the energy requirements of buildings and fuel consumption, and productive knowledge, understanding them to be universal measures of economic performance. Second, while the relationship between economic growth and individual welfare remains controversial, economic growth is still a significant factor to take into account when analysing ancient economies. Trying to approach economic performance at a larger scale and looking for larger trends and processes develops and complements our understanding of the Roman world. It frames issues such as resource distribution, organization of production and consumption, class formation processes, and other interactions between economic and social changes. Household approaches as proposed by Bowes (2021) have a high potential for addressing some of these questions, especially in combination with other methods. For example, landscape archaeology is indispensable in analysis of the economics of rural areas. Finally, while archaeological datasets are rarely as complete and representative as modern ones, multiple proxies can be and are often used in parallel to correct for the inherent incompleteness and biases of archaeological data. For example, proxies for economic growth can be contrasted with proxies for wealth distribution to establish how a society is changing and which groups reap the benefits, if any, of growth or contraction in the long term. In sum, while remaining critical of some of the assumptions ingrained in contemporary development economics and the data limitations, it is still valid and useful to measure economic growth in ancient economies and address large-scale models and questions.

Here, we explore the feasibility of testing a particular modern economic theory on the Roman economy through a multi-proxy approach. For the purposes of this review, we distinguish two classes of proxies: indicators of per-capita growth, and those that reflect an overall economic output increase (extensive growth), and which should be normalized by population size.

Proxies for Intensive Growth (Per-Capita Income Growth)

Per-capita or intensive growth denotes economic growth resulting from an increase in productivity, as opposed to an increase from a land grab, population expansion, or injection of capital. Several archaeological data types indicate increased productivity achieved through specialization (Fishman and Simhon 2002; Stigler 1951), economies of scale (Cleaver 2014, 81–83; Ethier 2009; Krugman 1979), and the introduction of new technologies and other innovations (Cleaver 2014, 79–81; Rosenberg 1963; Yu 1998). These three processes are often tightly coupled, meaning that their individual footprint in the archaeological record may be difficult to isolate. Nevertheless, any evidence for an increase in the productivity in agriculture and manufacturing implies per-capita economic growth. Here we focus on phenomena and processes related to economic growth that are particularly visible archaeologically (Table 4.1).

Craft Specialization

Specialization and division of labour leads to an increase in productivity through rising efficiency but is limited by the size of the market (Fishman and Simhon 2002; Stigler 1951). Although types of specialization, such as division of labour along gender and age lines, are common in all human societies, specialized craft production is a more recent phenomenon, often associated with early urbanization.

Evidence of specialized craft production as opposed to household self-reliance can be determined from several archaeological proxies, for example:

– bulk-produced goods, such as wheel-thrown pottery, e.g. most Roman pottery (Peña 2007; Romanowska, Lichtenberger, and Raja 2021);

– goods requiring specialized technology, such as pottery with slip or glaze or fired at high temperatures (De Vito and others 2014);

– existence of specialized workshops, such as fulleries (Flohr 2013);

– non-local distribution of craft objects, e.g. distribution of red-slip wares across the Roman Empire (Bes 2015; Carandini 1983).

Any measures of the proportions of craft products entering the archaeological record need necessarily to account for the availability of raw material, cost consideration, and the function of the objects. Since pottery preserves well, specialization in its production can be detected relatively easily, given

Table 4.1. Types of available archaeological data related to economic growth, with examples. Presence/absence refers to Boolean data; temporal distribution data refers to time-stamped measure of a given quantity; distribution data refers to the shape of distribution in a dataset; frequency data refers to relative prevalence of one or multiple classes of objects over other classes; spatial and spatio-temporal data refers to spatial distribution and any changes thereof; qualitative data refers in this context predominantly to written sources. Note that only one example of each proxy is given where many may exist.

Proxy	Data	Type of data	Example	Citation
Craft specialization	Presence of bulk, craft-produced goods, e.g. pottery	Presence/absence, frequency in site's assemblage	Distribution of Terra Sigillata in the Roman East. Pottery counts at Jerash	Bes 2015; Romanowska, Lichtenberger, and Raja 2021
	Goods requiring specialized technology to produce, e.g. high-temperature ovens	Presence/absence	Production of black-gloss wares in Punic Motya	De Vito and others 2014
	Existence of specialized workshops	Presence/absence	Fulleries in Pompeii	Flohr 2013
	Abundance of non-local, craft-produced products	Frequency in site's assemblage	African red-slip wares being exported all over the Roman West	Carandini 1983
	Counting the number of professions from different sources, archaeological, textual, or epigraphic, in a given site or sites	Frequency data	Number of professions in each Roman city	Hanson, Ortman, and Lobo 2017
Agricultural specialization	Existence of specialized rural sites	Presence/absence, frequency of similar sites, temporal distribution data, spatial distribution	Amphora and wine production sites in the Lower Llobregat Valley	Carreras, López Mullor, and Guitart 2013
	Specialized infrastructure	Presence/absence, frequency among sites, temporal distribution data	Wine and olive-oil presses	Marzano 2013a
	Evidence for infrastructure for the export of foodstuffs	Presence/absence	Roads, harbours, warehouses	De Vos 2013
Agricultural intensification	Evidence for irrigation systems	Presence/absence, frequency of similar sites	Cross-wadi walls, wells, *saqiyya* (a water-lifting device), waterwheels, dams, canals, kanats	Barker and others 1996
Production volume	Large productive rural sites	Presence/absence, frequency of similar sites	Villas, large pressing buildings	Marzano 2007
	High-capacity, specialized machinery	Presence/absence,	Massive milling complexes	Leveau 1996
	Size and number of workshops	Presence/absence, distribution data	Larger mill-bakeries or any other types of workshops	Bakker 1999; Murphy 2017
	Standardization of vessel size	Spatio-temporal distribution data	Mesoamerican Tuxtlas pottery	Arnold 1991
Innovation, technical advancement	Transition in technology	Presence/absence, chronology	Watermills replacing manual milling	Wilson 2020
Investment in capital goods	Significant presence of certain kinds of infrastructure	Frequency data, temporal distribution data, spatio-temporal data	Multiplication of the number of wine and oil presses	Marzano 2013b
	Written mentions and depictions of capital goods	Presence/absence, frequency data, temporal distribution data, spatio-temporal data	Mentions of water-lifting devices in Egyptian papyri	Malouta and Wilson 2013
Trade	Quantification of shipwrecks	Frequency data, spatio-temporal distribution	Change in the number of shipwrecks over time	Parker 1992; Wilson 2011b
	Evidence for long-distance, large-scale trade in ship cargoes	Presence/absence, frequency data, spatial data	Cargo compositions compatible with emporia-based trading	Rice 2016

Table 4.1. Types of available archaeological data related to economic growth, with examples *(continued)*.

Proxy	Data	Type of data	Example	Citation
Trade	Variety of commodities found in households	Presence/absence, frequency data	Homogeneity of goods among households	Smith 1987; Hirth 1998; Stark and Garraty 2010
	Quantification of imports	Presence/absence, frequency data	Abundance of imported goods in a settlement	Slane 2003
Monetization	Frequency of coinage in specific contexts	Presence/absence, frequency data	Abundance of coinage in a settlement	Birch and others 2019
	Distribution of coinage across time and space	Spatio-temporal data	Use of coinage in Temperate Europe before and after the Roman conquest	Howgego 2013
Urbanization	Measuring urban populations	Distribution data	Calculating population based on city size or calculating population density from house and household sizes	Hanson and Ortman 2017; Sinner and Carreras 2019
	Urbanization rate	Distribution data	Ratio of urban to rural population in Roman Italy	Lo Cascio 2009
	Comparing city-size distributions	Distribution data	Comparing Roman city sizes with other premodern societies	Wilson 2011a
Population size	^{14}C	Spatio-temporal distribution data	Time series of the number of ^{14}C dates in a given area	Riede 2009; Palmisano, Bevan, and Shennan 2017
	Extension of rural settlement into marginal areas	Spatio-temporal data	Expansion of rural sites in medieval Scandinavia	Lagerås 2014
	Measuring urban populations	Temporal distribution data	Calculating population based on city size or calculating population density from house and household sizes	Hanson and Ortman 2017; Sinner and Carreras 2019
	Rural populations from survey data	Temporal distribution data	Weighted settlement count	Witcher 2005; Fentress 2009
	Rural populations from written sources	Qualitative data	Estimated rural population densities from ancient accounts	Sinner and Carreras 2019
	Faecal stenols	Temporal distribution data	Variation of stenol levels in sediment over time	White and others 2018
Intensification of resource exploitation	Larger and more numerous resource extraction sites	Presence/absence, frequency data, distribution data	Increased quarrying around Aphrodisias	Long 2017
	Exploitation of new resources, such as new types of cereal, timber, fish, etc.	Presence/absence	Increased foraging	Morgan 2015
	Extension of rural settlement into marginal areas	Spatio-temporal data	Expansion of rural sites in medieval Scandinavia	Lagerås 2014
Consumption levels	Intentional refuse concentrations and their composition	Temporal distribution data, distribution data, frequency data	Refuse middens	Wilson 1994
	Variety and quantity of commodities found in households	Presence/absence, temporal distribution data, frequency data, distribution data	Variety of products, relative abundance of different kinds of products	Smith 1987; Hirth 1998; Stark and Garraty 2010
	Refuse in public contexts	Presence/absence, temporal distribution data, frequency data, distribution data	Variety of products, relative abundance of different kinds of products	Rowan 2017b
Individual wealth	Size, quality of construction, and decoration of buildings	Distribution data	Rank-size distributions of house sizes	Morris 2005
	Evidence for and proportion of luxury items in households	Presence/absence, temporal distribution data, frequency data	Count of luxury items in different houses	Smith 1987

Table 4.1. Types of available archaeological data related to economic growth, with examples *(continued)*.

Proxy	Data	Type of data	Example	Citation
Individual wealth	Expenditure in strictly non-utilitarian items, displays, and funerary practices	Presence/absence, frequency data, temporal distribution data	Frequency of costly items in burials	Bradley 1982
	Private evergetism	Presence/absence, temporal distribution data	Number of inscriptions over time	Wilson 2007
	Diversification in diets	Presence/absence, temporal distribution data, frequency data	Variety of products, relative abundance of different kinds of products	Rowan 2017a
Public expenditure	Size of the military and military infrastructure	Presence/absence, temporal distribution data	Fortresses in an area, fortress sizes	Verboven 2007
	Public infrastructure	Presence/absence, spatio-temporal distribution	Longitude and density of roads, aqueducts, and others	Carreras and De Soto 2013
Publicly funded events	Publicly funded events, civic and religious buildings, entertainment venues, nymphaea, and others	Presence/absence, qualitative data	Severan imperial beneficence financing buildings in Lepcis Magna	Ward-Perkins 1948
Written sources	Writings by ancient authors	Presence/absence, qualitative data	Mentions of economic performance or other economic phenomena	Terrenato 2012
	Epigraphical records	Presence/absence, temporal distribution data, frequency data	Tariff laws in Palmyra	Matthews 1984
	Documents, e.g. ostraca and papyri	Presence/absence, temporal distribution data, frequency data	Records of purchases and salaries from Roman Egyptian papyri	Harper 2016; Rathbone 2009

appropriate recording and full quantification. In general, when bulk-produced objects begin to appear in 'common' households it is a strong indicator for rapid growth in specialized craft production. This was the case of the Roman Empire, when almost all pottery was produced by professional craftsmen, and in many cases mass-produced (Peña 2007). While archaeologists can easily differentiate workshop-made from household ceramics based on their macro qualities, specialized technologies exist enabling more detailed analysis. X-ray powder diffraction and microscopy is used to characterize the chemical composition of pottery, and therefore the technology necessary for its production. For example, in the city of Motya, analysis showed considerable technological proficiency involved in the production of black-gloss wares at high firing temperatures in the sixth to fourth centuries BC (De Vito and others 2014). Further, high-quality, mass-produced pottery can be quantified to characterize its distribution. Andrea Carandini (1983) documented the large-scale distribution of African red-slip wares, indicating high specialization in the industry.

An alternative approach is to count specialized craft professions, attested archaeologically or in written sources, and their interdependence. This gives us an idea of just how specialized the workforce was (Hanson, Ortman, and Lobo 2017; Liu 2013; Ruffing 2016). More quantitative assessments, such as what percent of the workforce was involved in specialized craft, may be difficult to measure before census data becomes available in historical times. However, the existence of specialized tradesmen and craftsmen can usually be inferred through archaeological evidence or, where available, written sources. The professions of many craftsmen were attested in public inscriptions during Roman times. For example, J. W. Hanson, Scott G. Ortman, and José Lobo (2017) employed Jean Pierre Waltzing's (1895) list of professions for each Roman settlement, all inscriptions in the Epigraphik-Datenbank Clauss/Slaby, and Hanson's cities database (2016a; 2016b) to quantify the workforce of the entire Roman Empire. Archaeologically, workshops of specialized craftsmen are a feature of Roman urban economies, e.g. fulleries in Pompeii (Flohr 2013) or dye production facilities in Jerba (Fentress and others 2009). Besides finding tools and products, areas where specialized craft production took place can also be attested through geochemical analysis of sediments. For example, this technique was employed to locate an area of non-ferrous metalworking in medieval Riga (Banerjea and others 2017), demonstrating how combination of multiple available data can help with establishing which activities were present in a settlement.

Agricultural Intensification and Specialization

The *sine qua non* of urbanization is surplus production in foodstuffs, indicating agricultural intensification and specialization. Intensification increases productivity in a single plot of land through investment in irrigation and intensive working of smaller plots of land. It is often adopted as a risk management strategy (Marston 2011; Morrison 1994). Specialization means the landowner focuses on a limited number of crops or animals best suited to take advantage of the local conditions. Both strategies maximize productivity (Davies 2015). They are not mutually exclusive, and they can be attested archaeologically through:

- the existence of specialized rural sites, such as vineyards, catering for the population beyond the local area (Carreras, López Mullor, and Guitart 2013);
- the presence of specialized infrastructure, such as extensive irrigation systems, grain silos, mills, wine and olive-oil presses, and similar (Barker and others 1996; Rosen 2003; Marzano 2013a);
- evidence for medium- and long-distance trade in foodstuffs and for the necessary trading infrastructure involved, such as roads, harbours, warehouses, etc. (De Vos 2013).

Cèsar Carreras, Albert López Mullor, and Josep Guitart (2013) quantified Roman sites specializing in wine and amphora production in the area of Lower Llobregat, north-western Iberia, and showed a regional specialization in wine export. Similarly, Annalisa Marzano (2013a) tallied the number of sites equipped with presses for wine and olive-oil production around Rome, both villas and smaller farmsteads, showing they produced on a large scale to supply Rome's needs. Graeme Barker and others (1996) describe the economic transition related to the investment in irrigation infrastructure and reclamation of land in the Libyan Desert, and Steven A. Rosen (2003) describes a similar process in the Negev Desert, showing how intensification could be found in Roman times even in arid and semi-arid environments. Finally, Mariette De Vos (2013) show the link between agriculture and the infrastructure around Tugga, highlighting the importance of roads and transport infrastructure necessary to export the produce. All of these cases show a significant intensification and specialization of agriculture in Roman times, and how the trade of agricultural products was a significant driver for them. There are of course caveats. Specialization will not necessarily lead to increased output if there is a switch from intensive farming to more extensive practices. At the same time, intensification coupled with diversification might be adopted to reduce the risk of crop failure at the cost of lower output (Kandulu and others 2012).

Production Volume

Together with specialization often come economies of scale. A large workshop employing several specialists can reduce unit costs by increasing the output (Cleaver 2014, 81–83). An increase in the mean size of a production unit can be archaeologically recognized, for example, through:

- appearance of large rural sites housing infrastructure for the production of oil, wine, salted fish, etc. (Marzano 2007);
- change in the number and size of specialized machinery, e.g. number and size of oil presses, kilns, mills, metalworking facilities, etc. (Leveau 1996);
- increase in the size or number of workshops, food-production establishments, and similar (Bakker 1999; Murphy 2017);
- standardization of vessel sizes, e.g. storage or transport vessels (Arnold 1991).

The large mills at Barbegal (Leveau 1996) were clearly built to handle a large amount of grain. Milling on such a scale and making use of water power show the scale of food production in the area, and it would have been more efficient than using dozens of hand or animal-powered smaller mills. Jan Theo Bakker (1999) quantified the size and estimated the potential output of the mill-bakeries in Ostia and their evolution over time and found them to be larger and more productive than those in Pompeii. Large workshops, e.g. pottery workshops, are known from several locations, such as Sagalassos (Murphy and Poblome 2016; 2020). These workshops tended not to grow in size past a certain point, instead, it seems that these kinds of industries grew horizontally, adding new small workshops rather than enlarging existing ones beyond a certain point (Murphy 2017). The mere presence of a large workshop like these indicates a significant volume of production, enough to allow for specialization, and the more that can be found, the stronger the case for truly large-scale production driving economies of scale. In the countryside, villas and associated wine- and oil-production facilities are characteristic of Roman rural settlement throughout the empire (Marzano 2007). A high ratio of this kind of rural settlement means that agricultural production was more efficient, as these sites could contain the infrastructure necessary for the large-scale processing of wine and oil and other foodstuffs.

While larger-scale production of any given product is generally more efficient than small-scale production, differences in the level of specialization of the workforce involved and the amount of physical capital used are critical and must be taken into account when comparing different productive units before coming to conclusions regarding their effect on productivity (Atack, Bateman, and Margo 2008; Rosenberg 1963).

Innovation, Technical Advancement, and Investment in Capital Goods

Technological advancement and investment in capital goods increase productivity and enable large-scale specialized production (Cleaver 2014, 79–81). Equipment such as presses, watermills, and specialized machinery all increase efficiency and enable faster and more robust production processes but require upfront investment. In industrial economies such investment is known to be one of the main drivers of growth (Rosenberg 1963; Yu 1998), and it could be a good proxy for growth in the past as well, however keeping in mind its impact may differ in pre-industrial economies. Changes in technology and investment can be attested archaeologically, for example, in:

- a transition in technology, for example, from manual to machine production (Wilson 2020);
- significant presence of particular technologies or machinery, e.g. pressing infrastructure (Marzano 2013b);
- written descriptions and depictions of capital stock (Malouta and Wilson 2013; Wilson 2008).

Andrew I. Wilson (2020) quantified the number of recorded water-powered milling sites across the Roman Empire and, together with other instances of use of water power, concludes that a technology that appeared in the Hellenistic world was widely employed for the first time by the Romans to mechanize a time-consuming process. He associates this process with the general characteristics of Roman economy. Marzano (2013b) counted the number of multi-press facilities in Hispania, Gaul, and the Black Sea region and their evolution over time, finding they were widely employed from the first century AD onwards. An overall peak in capital investment in the first two centuries AD was followed by a sharp decrease after the fourth century AD. These examples show how investment in capital goods became increasingly widespread in the Roman economy and reinforce the argument for intense economic growth beginning in the early Roman Empire.

A problem regarding ancient machinery is that it is not always well preserved, e.g. mills and presses are easier to identify because their stone parts are preserved, but smaller screw presses or simple water-lifting devices are much harder to detect. This is where sources like written records can shore up our analysis. In Egypt, mentions of water-lifting devices in papyri are abundant and could be quantified to see their use over time (Malouta and Wilson 2013). However, written mentions are less common outside Egypt, making it more difficult to find direct evidence of capital investment at smaller scales.

Trade

Specialization, economies of scale, and intensification of production drive trade (Chaney and Ossa 2013; Cleaver 2014, 191–94; Ethier 2009; Fishman and Simhon 2002; Krugman 1979; Stigler 1951). It is necessary for supplying the raw materials to workshops but also as an outlet for the goods produced. Therefore, rise in traded goods is likely to reflect increased productivity, and with it per-capita growth.

Significant debate has taken place around the nature and scale of Roman trade over time,[2] and several measures aiming at estimating the volume of traded goods exist. Similarly, the *variety* of goods exchanged can be quantified. While luxury items are always profitable for trading, only larger markets and more specialized production can make cheap bulky wine or tableware profitable. Several archaeological types of evidence were used to estimate the volume and variety of traded goods:

- the volume of cargoes through shipwreck quantification (Parker 1992; Wilson 2011b);
- evidence for long-distance trade and for large-scale trade through identification of particular artefacts, such as tableware (Rice 2016);
- a change in the variety of commodities found in households (Hirth 1998; Smith 1987; Stark and Garraty 2010);
- quantification of imports in different settlements (Slane 2003).

2 For a summary, see Wilson and Bowman 2017.

Anthony J. Parker (1992) graphed dated Mediterranean shipwrecks, indicating a peak of shipping around the late first century BC–early first century AD. Wilson (2011b) updated the dataset and took into account changes in shipbuilding technology and cargo composition to propose a second-century peak in shipping. In both cases, shipwreck counts were employed as a proxy for trade volumes and general economic performance. Candace Rice (2016) studied a number of published and quantified Mediterranean shipwreck cargoes between the first century BC and the fourth century AD, revealing trading patterns compatible with emporia-based distribution and large-scale market exchanges. This finding is compatible with large-scale specialization, and therefore, intensive growth. The shipwreck data as virtually any archaeological data comes with its own challenges. Increasing ship sizes, better building techniques, perishable cargoes, different depths at which the wrecks are found, and the intensity of exploration of different coasts all bias the dataset significantly (Wilson 2009).

Focusing on households, Kenneth G. Hirth (1998) builds on Michael E. Smith's (1987) theories on household archaeology to detect patterns compatible with market exchanges in Mesoamerican societies. Through quantification and comparison of domestic assemblages, larger homogeneity among households reveals shared access to the same goods through the market.[3] At the settlement scale, the quantification of imported goods is vital to understand trade dynamics and what these might reveal about the local economy. In Roman Corinth, between the third and fifth centuries AD, imported mass-produced fine wares were so abundant that few were produced locally, showing a significant level of interconnectedness and specialization (Slane 2003).

Naturally, preservation biases can mask the variety and the patterns of traded goods. For example, artefacts have been so extraordinarily preserved in Berenike (Cappers 2006; Sidebotham, Hense, and Nouwens 2008) that they appear as varied in assemblages as those known from Rome, giving us an insight into the real variability of objects used. Additionally, not all movement of goods was always a result of trade. State involvement in the movement of goods has been well documented in the case of Baetic oil exported to Rome (Remesal Rodríguez 2018) and in Britain (Carreras 1998). The state-driven versus private-driven trade may be difficult to isolate from the overall distribution patterns.

Monetization

An increase in exchange may lead to monetization, which facilitates commercial transactions. Thus, the appearance of coins may herald a new phase in economic dynamics of a region, while the number of coins in circulation may indicate an increasingly trade-oriented specialized economy. Since this is rarely a topic in modern economics, the relationship between production, specialization, trade, and economic growth should be investigated further to establish whether coinage could be treated as a proxy for economic growth. This would be a particularly valuable indicator since coins are usually well published and in most cases come with a specific chronology. The topic has the potential to be advanced by:

- quantifying the ubiquity of coinage in specific contexts and in general (Birch and others 2019);
- establishing the distribution of coins across space and its changes over time (Howgego 2013).

Christopher Howgego (2013) detected monetization in pre-Roman economies through quantification and distribution of coinage. Elsewhere, the monetization of Japan in the late Tokugawa Shogunate was seen as symptomatic of a growing and increasingly mercantile economy (Yamamura and Duffy 1971). There are, however, many factors that affect coin minting beyond the purely economic, such as prestige or political reasons, so in isolation monetization is a less reliable proxy for intensive growth. Coin hoards in particular are especially difficult to interpret, since they can be a result of political instability, coinage debasement, or speculation (Crawford 1969), but their mere existence is a proof of an at least partially monetized economy.

Urbanization

The existence of urban populations necessitates specialization and exchange since a portion of the population is not producing their own food. Urbanization and, in particular, the densification of population facilitates specialization by creating larger markets and easing the distribution of goods (Fafchamps and Shilpi 2005; Stigler 1951). Archaeologically, the link between settlement nucleation and increased specialization, and therefore increased productivity, has been demonstrated among the pre-Hispanic Pueblo (Ortman and Lobo 2020). There, cooking wares were used as a proxy for population size, since their use depends on the number of people cooking and does not increase with income. The increas-

3 See Stark and Garraty 2010, for a similar approach and result for Andean societies.

ing ratio of fine wares to cooking wares evidenced increasing incomes, and the decreasing ratio of stone tools to cooking wares reflected increasing specialization in their production. This all happened as the population concentrated in larger, but fewer settlements. Therefore, per-capita growth must have been driven by agglomeration, given the lack of change in technologies used.

Measuring the size of urban centres and the general level of urbanization is an active area of study (Hanson 2016a). Some of the most popular measures are:

- estimating an urban population density based on written records, comparison with similar cities, population density and the city area, or by using an established mathematical relation derived from contemporary cities and their population (Hanson and Ortman 2017; Sinner and Carreras 2019);
- estimating the rate of urban to rural population (Lo Cascio 2009);
- comparing city-size distributions (Wilson 2011a).

While several methods exist for calculating urban populations, John Hanson and Scott Ortman (2017) put forward a simple method, based on the established mathematical relation between the size and the population of a city, and tested it on well-known ancient cities to estimate rates of urbanization in the Roman Empire. Elio Lo Cascio (2009) uses the urbanization rates of Roman provinces, that is, the percentage of people living in settlements above a certain population threshold regardless of juridical status, as a proxy for agricultural productivity. Comparing different estimates from different authors, he proposes a high productivity for Italian agriculture, comparable with early modern figures. Wilson (2011a) compares city populations and urbanization rates across different provinces of the empire and to other pre-industrial economies, concluding that either a very large overall population or a remarkable economic performance was necessary to sustain the large urban population of the empire. Finally, Hanson, Ortman, and Lobo (2017) directly link urbanization with the increase in specialization in the Roman economy, by comparing estimated city sizes with the diversity of professions documented in them and finding a correspondence between size and the diversity of trades.

While urbanization is quite uncontroversial as a proxy for economic performance, the relation might not be true in every case. In north-eastern Iberia, urban populations calculated using estimated densities and (when available) house sizes appear to be lower after the Roman conquest. This is not a result of population loss, since rural settlement expands significantly (Sinner and Carreras 2019). It is very likely that economic output increased because of a much more productive agriculture evidenced by the widespread implantation of villas economy and large-scale wine production (Carreras, López Mullor, and Guitart 2013). Contrasting urbanization with other proxies and known historical processes may be able to offset these issues.

Proxies for Extensive Growth

The proxies discussed above refer to the per-capita, i.e. intensive, growth. A less direct way of measuring economic growth is to look for proxies for extensive growth and then normalize them into per-capita growth using the population size. In simple terms, extensive economic growth results in larger economic output not because the processes became more efficient and productivity increased but because there are more people, more land, or more capital. For example, an intensification of agricultural production and its expansion over marginal land may be related not to changes in agricultural practices but to an increase in the number of farmers. If exploiting more land does not increase the amount of grain per capita, then there has been no per-capita economic growth even though the volume of the output increased. This is an important distinction because the EKC model focuses on per-capita economic growth and not extensive growth.

Measuring population growth in the past is in itself a dynamic topic of study (French and others 2021) with significant advances made in the last decade through modelling of settlement distributions, ^{14}C dates, and other proxies (Riede 2009). A recent study of Central Italy (Palmisano, Bevan, and Shennan 2017) found that ^{14}C date counts and site count and other site-derived population proxies seem to covariate, meaning they are all potentially reliable population proxies. For medieval Scandinavia, the extension of rural settlement into marginal areas has been proposed to reflect demographic growth (Lagerås 2014). In Roman archaeology, researchers have focused on determining the urban population sizes, and to a lesser extent rural populations. For rural populations, Elizabeth Fentress (2009) adapts a method employed by Robert E. Witcher (2005) to calculate the size of rural population from survey data, by estimating populations for different types of sites. Of course, the relation between survey data and the reality of settlement is complicated (Mattingly 2009), but the relative changes and general trends within a well-defined chronological frame can be estimated. For example, Alejandro G. Sinner and Cesar Carreras (2019) relied on written sources, extrapolating from Pliny's figures for north-western Hispania Tarraconensis (Plin., *HN*, III. 3. 28) a rural population density, and then compared it with earlier proposals for rural population densities in other provinces, finding them to be similar. When available, written sources might be of use, but such mentions are rare and notoriously unreliable. New methods are continuously being developed. For example, for a more situational population proxy, Adam J. White and others (2018) used faecal stanols, which have been shown to reliably track population change in Cahokia, Illinois.

Intensification of Resource Exploitation

When changes to the population size are controlled for, a number of phenomena can be related to economic growth. A more intense exploitation of the natural resources that is not linearly dependent on population size can indicate a higher level of economic activity. It can manifest itself in a number of ways:

- larger and more numerous resource extraction sites, such as mines or quarries (Orejas and Sánchez-Palencia 2002);
- exploitation of new resources, such as new types of cereal, timber, fish, etc. (Morgan 2015);
- extension of agricultural zones onto marginal terrain (Lagerås 2014).

In Aphrodisias, Leah E. Long (2017) argued that more and larger quarries and mines surrounding the city indicate more economic activity during certain periods. In Carthago Nova, south-eastern Hispania, mining was a dominant industry which enriched local elites significantly, evidenced by epigraphy, which shows that republican families linked to mining constituted the backbone of local aristocracy under the empire (Orejas and Sánchez-Palencia 2002). Ben Russell (2013, 352–59) more generally linked the stone trade with private actors in a market economy and highlighted how the growth and decline of the stone trade in the Roman Empire show the same long time trend that other indicators show for trade. Regarding non-mineral resources, the idea of intensification driven by population pressure and resulting in falling returns has long been proposed for agriculture (Boserup 1965), and more recently a similar concept has been applied to other resources in hunter-gatherer societies (Morgan 2015). It would not be difficult to apply this same concept to non-agricultural resources, like wood and fishing.

Consumption Levels

Another proxy for gross economic growth is an increase in consumption unrelated to population growth. A more productive economy, more income, or higher standards of living will manifest themselves in more consumption, although this needs to be checked against any changes in population size. There are many ways of measuring consumption usually focused on monitoring volumes of objects, which consistently accumulated over time, such as pottery or alternatively studying the variety of products in use in a given context and period. These can be aggregated in different archaeological contexts:

- intentional refuse concentrations, e.g. refuse middens or dumpsites, where refuse was discarded on a regular basis (Wilson 1994);
- private household contexts, e.g. by studying the volume and variety of objects present in households or proportion of households with access to a specific category of goods, such as luxury goods (Smith 1987);
- public contexts, e.g. spaces where refuse accumulated, for example, sewers or backfills of disused structures, such as old cisterns (Rowan 2017b).

Refuse middens can provide an insight into consumption patterns (Wilson 1994). In Berenike and its surroundings, the excavation and quantification of dumpsters and refuse middens provided ample information on the consumption patterns of its inhabitants and the growth and decline of the city's economy (Cappers 2006; Wendrich and Sidebotham 2007). The site of Monte Testaccio, Rome's grand amphora hill, preserves a unique record of oil consumption and state expenditure (Remesal Rodríguez 2018). In Pompeii and Herculaneum, Erica Rowan (2017b) studied the botanical remains in sewers finding evidence for increasingly diverse diets of their inhabitants.

Such refuse accumulations are not always easy to identify, and in particular to date reliably, which limits their utility for estimates of consumption volumes and patterns over fine-grained chronology. Additionally, sewers and public spaces were regularly maintained to enable their functioning, meaning the refuse accumulated there will mostly correspond to late phases of use.

Measures of Individual Wealth and Social Stratification

An increase in the standard of living, changes to the average wealth of individuals, or indicators of expendable income may be a result of per-capita economic growth. These kinds of changes are visible archaeologically, for example in:

- size, quality, and decoration of buildings (Flohr 2017; Morris 2005);
- presence and proportion of luxury and exotic items (Smith 1987);
- evidence for increasing expenditure on non-utilitarian (in the strictest sense) items, for example related to rituals, costly displays of status, the funerary sphere, etc. (Bradley 1982; Langdon 2005);
- private evergetism (Wilson 2007);
- diversification in diets, not related to nutritional needs (Rowan 2017a).

House-size studies have been carried out in many ancient cities, such as Pompeii (Flohr 2017) and ancient Greek poleis (Morris 2005). Ian Morris in particular sees the growth in house sizes as indicative of long-term economic growth. Modern households increase the variety of commodities as their income increases (Jackson 1984). Likewise, excavated ancient households with more, more varied, and costlier commodities will reflect a higher income, as proposed by Smith (1987). The non-utilitarian discard of costly items in the funerary sphere has also been approximated to economic performance in prehistoric Europe (Bradley 1982; Langdon 2005). Cost can be measured in work hours and the scarcity of the resources necessary to produce an item. Private evergetism and urban development projects, measured by the number of inscriptions, have been proposed to reflect episodes of economic growth in Timgad (Wilson 2007). Rowan (2017a) studied diets and household consumption from the remains preserved in Pompeii and Herculaneum's sewers, linking them to nearby houses and documenting a relatively high standard of living.

However, any of the above measures of individual wealth may equally be a reflection of inequality (Milanovic, Lindert, and Williamson 2007; Scheidel 2016; 2020). As the original Kuznets Curve model proposes, the relation between economic growth and individual wealth is not linear, and the benefits of growth are rarely evenly distributed. This makes measures of individual wealth useful only in cases where inequality can be controlled for (in effect this means where the proxies for individual wealth are available and representative for most of the community) and where the socio-cultural context, for example in relation to social display or religious rituals, is considered (Rissman 1988). Otherwise, only very general conclusions can be drawn on the basis of such proxies.

Administrative Structure and 'Public Wealth'

In modern societies, state expenditure often increases together with a growing economy, as tax revenue grows. According to Wagner's Law, the public share of the economy grows proportionally to income, though this might no longer be true in the last decades (Kuckuck 2014). In turn, public expenditure on infrastructure can ease trade and facilitate production, thus stimulating growth. Past taxation systems differed significantly from the modern one, but several archaeological proxies can indicate state expenditure:

- size of the military and military infrastructure (Verboven 2007);
- investment in public infrastructure, such as aqueducts or roads (Carreras and De Soto 2013);
- publicly funded events, civic and religious buildings, entertainment venues, nymphaea, and others (Ward-Perkins 1948; Wörrle 1989).

Besides being a proxy for a larger economy, state expenditure can directly lead to increased economic activity, as was most certainly the case around military bases in the frontiers of the Roman Empire (Verboven 2007). The road network built by the Roman state (Carreras and De Soto 2013) also had a positive effect on the economy of the provinces. In the Roman world, private evergetism was the main source of funding for the construction of public and civic edifices, but the local authorities could also occasionally finance certain buildings or events (Wörrle 1989). What could be argued is that imperial evergetism reflects public expenditure, since in practice the coffers of the emperor and those of the state were not separate. Therefore, imperial beneficence such as the Severan embellishment of Lepcis Magna (Ward-Perkins 1948) could be considered public expenditure.

Similar to the measures of disposable income in individual households, the state's 'disposable income' does not correlate linearly with economic growth. Disentangling factors involved in taxes, state income, and expenditure requires significant contextual information. For example, after the third-century crisis state expenditure increased to face military threats, leading to coinage debasement and inflation

(Howgego 2013). An increasingly sophisticated administration devoted to collecting taxes was then set up to shore up a failing economy (Prodromidis 2009). Again, most conclusions based on proxies related to public expenditure and structure would be general in nature, for example, the presence/absence of tax administration is an indication of a different level of economic framework, even if its size may not be reliably estimated on its basis alone.

Written Sources

Finally, written records are an important source of information regarding the state of the economy, especially for later periods of history. In Antiquity, interpreting written sources is difficult due to the unsystematic manner in which most of them were produced. This combined with the difficulty of dating inscriptions and other epigraphic material, means that the snippets of the past provided by specific documents, although often highly detailed, can rarely be extended beyond their immediate context. General observations and contextual information that may help to interpret other data sources can be derived from:

- ancient authors, e.g. Cato (Terrenato 2012);
- epigraphical records (Matthews 1984);
- documents found in ostraca and papyri (Harper 2016; Rathbone 2009).

Ancient authors rarely go into detail about the functioning of the economy beyond general observations, but they are useful for illustrating technical processes, organization, and administration of certain aspects of the economy. For example, Cato's *De agricultura* gives us an insight into the organization and functioning of an idealized agricultural centre (Terrenato 2012). Epigraphical records can serve as evidence for the existence and relative importance of certain economic activities. For example, the Palmyrene Tariff laws give an idea of the variety and magnitude of trade there, both with the city's hinterland and beyond (Matthews 1984). More systematic evidence, for example on papyri and ostraca, enabled reconstructions of price, rent, and wage series in Egypt (Harper 2016; Rathbone 2009).

Environmental Proxies

Although humans have always polluted their immediate surroundings, for most of prehistory the generally low density of settlements and the predominant use of organic materials and low-impact style of life meant that, with a few exceptions, the human impact on the environment was limited outside of major urban centres. The exceptions to this rule are the large-scale land clearing for agriculture, soil erosion and degradation, and localized pollution related to industrial activities such as mining or metalworking. It is urbanization, however, that brought about the first noticeable increase in the rate of environmental degradation.

For example, Richard Sallares (2007, 24) discusses how in the Roman times the highest level of environmental degradation must have occurred in the immediate surrounding of urban centres and during periods of intensification of settlement. He draws an association between a significant increase in the rate of soil erosion and growth in settlement density in Latium during the second century BC. These farmsteads served as the hinterland to the rapidly expanding city of Rome.

Archaeological proxies for human-caused environmental degradation (Table 4.2) can be roughly divided into direct measures of the impact (levels of pollutants, soil erosion, deforestation, etc.) and indirect measures derived from osteological material or inferred from behavioural changes (e.g. abandonment of an area). The latter are more difficult to interpret as the weight of environmental impact is often difficult to extricate from the tangle of individual motives behind behavioural shifts.

Direct Evidence of Environmental Impact

Heavy Metal Pollution

Metal mining and smelting are a primary cause for heavy metal pollution, sometimes extending over large areas. The fluctuating levels of lead, mercury, cadmium, zinc, and other pollutants can be reliably measured and serve as chronologically controlled archives of human-related environmental impact (Bindler and others 1999; Cooke and others 2020; Martínez Cortizas and others 2000). Their concentrations were detected in a variety of strata:

- peatbogs (Martínez Cortizas and others 1999);
- soils (Bindler and others 1999; Rouhani and Shahivand 2020);
- tree rings (Bindler and others 1999);
- lake sediments (Cooke and others 2009);
- ice cores (Hong and others 1996; McConnell and others 2018).

Table 4.2. Types of available archaeological data related to environmental degradation, with examples. The presence/absence refers to Boolean data; time-series data refers to a time-stamped measure of a given quantity; distribution data refers to the shape of distribution in a dataset; frequency data refers to relative prevalence of one or multiple classes of objects over other classes; spatial and spatio-temporal data refers to spatial distribution and any changes to thereof. Note that only one example of each proxy is given where many may exist.

Proxy	Data	Type of data	Example	Citation
Heavy metals pollution	Lead, mercury, cadmium, zinc in ice cores	'Global-scale' time-series data	Changes to the levels of lead in Antarctic ice cores over the last millennia	McConnell and others 2018
Local heavy metals pollution	Lead, mercury, cadmium, zinc in peatbogs, soils, tree rings, lake sediments	'Local-scale' time-series data, spatio-temporal distribution	Levels of lead and mercury related to industrial activity in NW Iberia	Martínez Cortízas and others 2002
Soil degradation and pollution	Soil salinity	Distribution, spatio-temporal distribution	Levels of salinity in ancient field systems in semi-arid regions	McCool and others 2018
	Isotopes, trace elements, biomarkers, etc.	Frequency, presence/absence, spatial distribution	Presence of biomarkers of manure	Bull and others 1999
Soil erosion	Geomorphological data	Spatio-temporal data	Geomorphological sequences and spatial distribution of deposition layers in Greece	van Andel, Zangger, and Demitrack 1990
	Geomagnetic, seismic, and geochemical data	Spatio-temporal data	Composition of lake sediments enabling environmental reconstructions	Curtis and others 1998
Deforestation	Pollen profiles	Time-series data	^{14}C-dated pollen profiles showing local landscape evolution in the Black Forest	Rösch 2000
	Charcoal analysis	Time-series data, spatio-temporal distribution	Pollen and charcoal sequences reconstructing land clearance through forest burning in New Zealand	McWethy and others 2009
Water over-exploitation	Evidence for irrigation systems	Presence/absence data from excavations and written sources	Legislative texts related to irrigation in the Roman law	Wilson 2012
Water pollution	Geochemical analysis	Levels of nitrates, ammonia, chloride, sulphates, and other pollutants	Sampling of water sources and sediments	Luzzadder-Beach 2000
	Biomarkers	Presence/absence, frequency	Detection of biomarkers indicating contamination in latrine sediments	Mitchell, Stern, and Tepper 2008
Greenhouse gases	CO_2, methane levels in ice cores	Time-series data	Levels of greenhouse gases detected in Antarctic ice cores	Ruddiman 2007
Life expectancy and health impact	Osteological analysis	Distribution	Population analysis of age profiles at cemeteries	Chamberlain 2006
	Geochemical and DNA analysis	Presence/absence, distribution	Levels of heavy metals in skeletal material from the necropolis of A Lanzada	López-Costas and others 2020
Depopulation and deurbanization	Settlement analysis	Spatio-temporal distribution	Reconstruction of fluctuations in population density in Central Italy	Palmisano, Bevan, and Shennan 2017

For example, the investigation in Galicia, north-western Spain, has revealed peatbog sequences spanning the last four thousand years (Martínez Cortizas and others 2000; Martínez Cortizas and others 2002). They show significant peaks in lead and mercury levels during the Roman Empire, almost certainly related to mining activity in the cinnabar mines of Almadén, where mercury was used in vermilion production. Interestingly, this peak of the anthropomorphic generated mercury pollution, although significant, did not extend beyond the range of naturally occurring concentrations (Martínez-Cortizas and others 1999).

These kinds of sequences are not available everywhere. For example, the majority of European peatbog sites are located in the northern part of the continent (Martínez Cortizas and others 2000, 1), but in areas where they do exist they could become an important source of information on heavy metal pollution. So far, these sequences are collected with a view to recording net accumulation of lead, mercury, and other heavy metals over century-long scales, but finer sampling and calibration could provide more detailed sequences. Since there are several alternative types of such 'natural archives', the particularities of their specific depositional and post-depositional contexts can be overcome through comparison and calibration against each other. The reconstruction of the continental-scale record of anthropogenic heavy metal pollution is currently advancing at a rapid pace, providing further evidence for the presence of heavy metals in the environment. (Cooke and others 2020).

Soil Degradation (Reduction in Soil Fertility and Soil Pollution)

Another form of anthropogenic environmental degradation is soil degradation. It implies the loss of fertility and the contamination of the soil, and can take many forms. Over time, the nutrient content of cultivated soil deteriorates leading to crop yields decreasing year after year. Additional, household, agricultural, or industrial activities can spread chemicals that can further damage fertility and create health hazards. In extreme cases, intensive exploitation can lead to irreversible damage, soil erosion, desertification, etc. Soil degradation and pollution can be recorded through:

- electrical conductivity to detect salinity (McCool and others 2018);
- isotope studies (e.g. nitrates) (Canti and Huisman 2015);
- faecal biomarkers (to detect manure) (Bull and others 1999);
- geochemical multi-element analysis of agricultural soils (nutrient reduction, pollution) (Canti and Huisman 2015; Oonk, Slomp, and Huisman 2009);
- geochemical analysis of soils to detect pollution in domestic and industrial contexts (Oonk and others 2009).

Soil salinization is of particular concern to areas of the world with limited rainfall since it can render the soil unsuitable for agriculture. For example, Michal Artzy and Daniel Hillel (1988) argue that this process was responsible for significant soil degradation in southern Mesopotamia. Graeme Barker (2002) describes the soil contamination caused by heavy metals pollution seeping from the nearby mines and metallurgical workshops in Wadi Faynan, Jordan, during Roman times. The decrease of soil productivity due to the contamination was further aggravated by the destabilization of the water system caused by forest clearing associated with the high demand for timber by local industry. In the end, the area succumbed to the process of desertification and agricultural activity had to be abandoned.

Besides measuring the scale of soil degradation, we can also archaeologically record strategies adopted by farmers to counteract this process:

- extensive agriculture, leaving the fields fallow for up to thirty years between cultivation;
- crop rotation, where from one year to another fields are used for different types of crops and for pasture and crop diversification, where, for example, legumes are grown alongside cereal;
- artificial fertilization, which implies a close coupling with animal husbandry necessary for manure.

Different types of soils will have different nutritional content and suitability for crops, thus their fallow time or ability to rotate crops may differ. In general, extensive agricultural practices involving decades-long fallow periods are only possible in areas of very low population density. Once the population reaches a certain threshold it is not feasible to follow the slash-and-burn strategy, as it requires high mobility of households and large unoccupied areas. Crop rotation is a highly successful agricultural strategy. Here the remnants of the fields would show more permanence, through ridge-and-furrow structure or permanent or semi-permanent field boundaries. Finally, faecal biomarkers can reliably detect past manuring making this agricultural strategy archaeologically attested (Bull and others 1999).

Detecting soil contamination with heavy metals and other pollutants is one of the most direct measures of environmental degradation and should, in principle, be applicable to the majority of sediments. Measuring soil degradation due to over-exploitation and nutrient reduction is more difficult to achieve, and the impact of natural factors, such as droughts, can be hard to isolate.

Soil Erosion

Soil erosion can have a serious impact on the local population through degradation of the agricultural potential of the area, catastrophic mudslides and floods, slope collapses, silting up of aquifers, and other adverse events, such as dust storms. The main anthropomorphic causes of catastrophic soil erosion are all related to agriculture and its intensification: deforestation, expansion of agricultural activity to the uplands, grazing, and damage to terraces — all of which can be aggravated by natural processes (Lichtenberger and others 2019; 2021; Holdridge and others 2017). As a result, gullies form and the resulting surface run-off can strip any soil remaining on slopes (van Andel, Zangger, and Demitrack 1990; Attema 2017). A closely related issue was sediment deposition causing areas to become marshland — breeding grounds for mosquito populations and malaria vectors (Walsh, Attema, and de Haas 2014). Erosion rates are primarily detected through geological and geomorphological analysis of sediments such as:

- geomorphological analysis of alluviation, river aggradation, layers indicating intense periods of silting up, and colluvial deposits (van Andel, Zangger, and Demitrack 1990; Wiseman 2007, 100);
- seismic analysis of sediment volume and geometry (Anselmetti and others 2007);
- magnetic susceptibility, oxygen and carbon isotopes, and other geochemical indicators (Curtis and others 1998);
- Pottery-sherds distribution (James, Mee, and Taylor 1994).

Untangling the natural from the anthropogenic factors in the sedimentological history of a region is a difficult task. Climate fluctuations can closely mimic human-induced degradation and in many cases their impact can be short and localized, when intense weather events trigger catastrophic events. In addition, there is a high level of uncertainty related to the dating of alluvial and colluvial deposits. It is however possible to overcome many of these challenges by multi-method dating of the sediments and by comparing multiple environmental proxies, including oxygen isotopes (Curtis and others 1998).

There has been a long-standing debate on the relative importance of climate versus human impact on the evidence for soil erosion around the Mediterranean during the Holocene.[4] The periods of land erosion and stability have been attributed predominantly to anthropogenic factors by Tjeerd H. van Andel, Eberhard Zangger, and Anne Demitrack (1990), who argue that regional sequences show little similarity to each other indicating local rather than regional or global climate phenomena, a view contested by Alfred Thomas Grove and Oliver Rackham (2003).

Soil erosion, if kept unchecked, can lead to the total abandonment of an area. The site of Stobi in Macedonia (Wiseman 2007) is a good case in point. The well-documented alluvial deposits and dust layers caused by soil erosion and aggravated by climate change correlate with the increasingly desperate attempts of the inhabitants to protect their livelihoods and the ultimate abandonment of the once thriving city. Similar processes occurred in many other regions, e.g. in the cities of Halieis, Hermion (van Andel, Zangger, and Demitrack 1990), the Biferno Valley (Barker 1995), Malta (Hunt 1997), and the Pontine Plain (Attema 2017), among others.

Flavio S. Anselmetti and others (2007) compared the rates of erosion with palynological data and reconstructed population numbers in the region of Petén, Guatemala. Here the relationship between population growth and soil erosion was not linear. The highest rates of soil erosion correlate with periods of land clearing but precede peaks of population density in the region. Similar studies could establish whether this is a general trend or a process specific to this case study.

Deforestation

Deforestation has been one of the most extensively investigated types of human environmental impact. The most famous case studies of large-scale deforestation, including Rapa Nui, Mayan Lowlands (Anselmetti and others 2007; Rue 1987), and New Zealand (McWethyand others 2009), show a dramatic impact on the local environments and populations, but even in low-profile cases a transformation

4 For a summary, see Wiseman 2007.

in the local land cover can result in changes to local hydrology, soil erosion and depletion, and reduction of key resources, such as fuel. Human-caused deforestation occurs through land clearing for agriculture and through resource exploitation since timber is required for a range of domestic and industrial activities, such as cooking, heating, smelting, and construction (Kaplan, Krumhardt, and Zimmermann 2009). Changes in the local vegetation cover can be detected directly through:

– pollen profiles (McNeil, Burney, and Burney 2010; Rösch 2000);
– charcoal analysis (McWethy and others 2009; Miller 1985).

Jed O. Kaplan, Kristen M. Krumhardt, and Niklaus Zimmermann (2009) used a somewhat different approach to study deforestation. By coupling population-number estimates with data related to soil quality and other agricultural indices the authors simulated the local deforestation-depopulation-regrowth cycles in Europe over the last three thousand years. This type of modelling, perhaps coupled with palynology could be equally applied on a local and regional scale.

Deforestation is a known factor in soil erosion, especially when combined with intensive agricultural exploitation (Anselmetti and others 2007). For example, E. S. Deevey and others (1979) describe a scenario where deforestation resulting from the need for construction material for the city of Yaxha, Guatemala, combined with agriculture necessary to feed its rapidly increasing number of inhabitants triggered mass soil erosion and slopewash, which limited the city development. Similar examples of progressing deforestation are known from other sites and periods (e.g. Mikesell 1969; Andrieu-Ponel and others 2000).

Water Over-Exploitation

Water management in areas where water is a scarce resource is likely one of the oldest attempts of human communities to counteract their negative impact on the environment and to regulate their behaviour to ensure sustainability. In arid and semi-arid areas over-exploitation of water sources impacts food supply and therefore the feasibility of human occupation. Many past societies developed complex infrastructures to stabilize water supply and prevent crop failure, or even desertification of their land.

Archaeological proxies for over-exploitation of water are mostly related to the actions undertaken by societies to counteract it:

– appearance of water management infrastructure (see Wilson 2012 for a summary as well as the papers in Wilson 2012);
– shift in farmed species to those with lower water requirements;
– abandonment of an area.

It is difficult to separate human stressors on water resources from their natural fluctuations. Because water shortages may stem from short-term (droughts) and long-term (climate change) natural phenomena, it is not easy to control for these external factors.

The appearance and distribution of certain water management structures may be indicative of water stress. For example, kanats are ancient underground tunnels providing access to distant water sources located upland from the settlements. The earliest examples date to the first millennium BC, and in Antiquity, they were distributed across the arid zone stretching from Spain to China. They are inherently sustainable as they only draw recharged water from an aquifer and do not affect the water table, and are therefore recognized as a potentially sustainable solution to the issue of over-exploitation of water resources in the region (Manuel, Lightfoot, and Fattahi 2018).

Water Pollution

Water supply is a critical resource for any human group, and its contamination has implications for drinking water availability, the health of the local population, agriculture, and the wider environmental setting (Hudson-Edwards 2018). Groundwater quality may be a limiting factor for the local population (Luzzadder-Beach 2000) if other sources of fresh water are limited. Human waste in the form of sewage is one of the most dangerous forms of pollution being responsible for outbreaks of cholera and other diseases. Even if the risk of disease from contaminated water is not realized, people have an innate predisposition to avoid human waste, making this type of pollution more 'visible'. Sewage was an important issue in urban areas as evidenced by the construction of sanitation infrastructure in urban centres, a good example of which are Rome's sewers. Many types of pollution affecting soils and air can also contaminate water, for example, heavy metal pollution from mining activities.

Water can be analysed for:

- nitrate and ammonia indicating contamination from manure and possibly sewage;
- chloride, which impacts crops and limits the feasibility of some of them;
- sulphate, which if it exceeds safe levels renders water non-potable;
- electrical conductivity to measure the levels of minerals (calcium, magnesium) and the suitability of water for agricultural purposes (Luzzadder-Beach 2000);
- trace metals signalling industrial pollution (Baptista Neto and others 2017);
- biomarkers such as remains of parasites and proteins produced by microorganisms found in cesspool sediments (Mitchell, Stern, and Tepper 2008);
- pollution (heavy metals, phosphates, cyanobacteria) affecting drinking water (Lentz and others 2020).

Antonella Cattaneo and others (2004) analysed the changes in diatom morphology and diversity in the sediment core to reconstruct the impact on heavy metals from local mines operating since the early twentieth century around the lake Lac Dufault in Canada. The method could be applied to any sediments where diatoms are preserved. The work by Piers D. Mitchell (e.g. Mitchell, Stern, and Tepper 2008) demonstrates that latrine sediments can be successfully analysed for a wide range of parasites, such as tapeworm and disease-causing microorganisms likely originating in contaminated water. A comprehensive multi-proxy analysis (Lentz and others 2020) combining several geochemical and biological markers in the sediments related to the water reservoir of Tikal indicates that the heavy metal, phosphate, and bacterial pollution endangered the city's potable water supply and likely contributed to the ultimate abandonment of the city.

CO_2, Methane, and Other Greenhouse Gases

The proponents of the early anthropogenic hypothesis (Ruddiman 2007) argue that the Holocene fluctuations in atmospheric CO_2 and methane recorded in ice cores might be human-induced, pointing to the wide deforestation related to land clearing for farming and an increase in the numbers of methane-producing cattle. In this scenario, the interglacial-like conditions experienced by humanity in the last five thousand years are caused by the onset of farming which blocked an impending glacial period. This view has been criticized on the grounds that the human impact would be minimal compared to natural sources of greenhouse gases (e.g. Pongratz and others 2008). Although climate change is a primary cause for concern nowadays, it is unlikely that people in the past would be able to record long-term climate fluctuations or link them to their behaviour.

Impact on Humans as Environmental Proxy

Environmental degradation is often most noticeable through its impact on people and their health. Human skeletal material is archaeologically visible and, in most projects, retained, making it available for a wide range of analyses even if it was excavated decades ago. Although not all diseases leave traces on the osteological material, increasingly sophisticated techniques including protein and ancient DNA analyses are enlarging the scope of information that can be retrieved from human remains. Population-level analyses of cemetery data can reveal shifts in mortality profiles signalling environmental stressors although the challenge of establishing a detailed chronology that would enable detection of short-term population fluctuations remains for most archaeological sites. Finally, landscape analysis shows patterns of abandonment and migration that could be caused by environmental degradation. These higher levels of analysis come with a challenge of establishing the role of environmental degradation in population changes as opposed to other factors. For example, a drop in life expectancy may be caused by historical events, environmental stressors due to natural processes, or internal social dynamics. Determining which factors have had the most significant impact requires adequate contextual data.

Decrease in Life Expectancy and Specific Health Issues

Several environmental indicators, both biological in origin (patogenes) and trace elements can be measured directly in human remains. For example, the levels of mercury and lead in human bones are a good proxy for the individual's exposure to heavy metals but also indicate the pervasiveness of heavy metal pollution in the surrounding environment (Álvarez-Fernández, Martínez Cortizas, and López-Costas 2020; López-Costas and others 2020). Both lead and mercury easily accumulate in the food chain and in the human body and are highly toxic. Possible reasons for high levels of exposure are related to mining and metallurgy, but the atmospheric concentration of these heavy metals would impact the whole population. Similarly, biological markers of diseases can be detected directly in human remains, serving as a proxy for environmental degradation typical for urban centres, such as poor sanitation, water contamination, etc. Further, changes in population-level mortality profiles when large osteological datasets are available can be used as proxies. Epidemics of acute diseases have a high dependency on population density making urban areas particularly at risk. With progressing urbanization their impact on the general population would have increased over time. For example, although earlier epidemics are known, the Antonine Plague and the Cyprian Plague were unprecedented in their geographical range as they spread between the Roman urban centres. There are numerous types of analysis that can reveal environmental degradation, most promising among them:

- heavy metal (lead, mercury) content in bones (López-Costas and others 2020) and arsenic in hair (Kakoulli and others 2014);
- presence of pathogens, e.g. detected through ancient DNA (Devault and others 2014);
- population-level indicators, e.g. macroscopic consequences of pathogens and exposure to toxic substances, population characteristics, such as decrease in average height, and mortality profiles (Chamberlain 2006).

Olalla López-Costas and others (2020) observed that during Roman times atmospheric pollution was responsible for almost 60 per cent (in some cases up to 85 per cent) of lead contamination in the bones of the population at the necropolis of A Lanzada, Spain. The findings have also agreed with the local sequences of atmospheric heavy metal levels (see section Heavy Metals Pollution, above) indicating that human bones can be used as another type of 'natural archives' preserving the record of past pollution. This is of particular interest since isotopic analysis is routinely performed on osteological material.

Settlement Abandonment and Changes in Adaptation Patterns

Another indirect proxy for environmental degradation is behavioural change on a population level such as abandonment or shift in subsistence strategies. This can be framed at different scales of analysis: from a higher rate of individual households' movement over the mosaic-like landscape of fallow and active fields to the discourse of civilizational collapse, including depopulation through migration, demographic decline, or abandonment of entire cities. In almost all cases, the impact of natural and anthropogenic environmental pressure is at least considered as a possible reason. The most common scenario invoked is one of over-exploitation of natural resources, often coupled with a demographic boom that leads to overshooting the carrying capacity and subsequent collapse.[5] Abandonment at a population level can be archaeologically attested through:

- depopulation — decrease in the number of archaeological remains of settlements, households, artefacts, ^{14}C dates, and other measures used to infer population size (Palmisano, Bevan, and Shennan 2017; White 2017; Turchin and Scheidel 2009);
- urban decline — complete desertion or decrease in the size and number of urban centres;
- large-scale change in subsistence strategies (e.g. move from sedentary lifeway to pastoralism).

On a regional and local level, abandonment can manifest itself in:

- shorter average occupation of sites;
- change in subsistence strategies (e.g. from slash and burn to intensive agriculture, exploitation of marginal zones) (Lagerås 2014);
- change in resource exploitation (e.g. shift in crops planted or species hunted).

Here again, external factors, such as natural climate fluctuations or historical events as well as the internal dynamics of a group constitute confounding factors. The branch of science concerned with resilience, both in the past and present communities, is a rapidly growing field (Redman 2005; Redman and Kinzig 2003), and with continuously increasing numbers of new datasets it may be possible to control for some of the external factors.

5 For a discussion on different forms of 'collapse', see Middleton 2012; Redman 2019.

The Case Study of Palmyra

The aim of the case study is to highlight the difficulties related to obtaining relevant data through an example of an archaeological site with a rich history of archaeological research and with, at least in theory, a great potential to derive both economic and environmental proxies. Although, as the examples given above showcase, it is possible to use a wide variety of archaeological material as economic and environmental indicators, in practice this is often far from a straightforward task. While one might criticize using a single case study, or one that is not exhaustive, we believe that it is valuable to critically assess the level of accuracy and detail that can be derived from a representative archaeological site, of a kind which often provides data upon which models about the Roman economy are based. Although the discussion of the fragmented nature of such evidence is far from new, here we offer a set of potential pathways for increasing reliability of archaeological data: multi-proxy approaches, quantification, wider use of formal and analytical methods in comparative studies, including for theory testing, and finally, the creation of a more robust baseline by combining multiple case studies. Our argument is that in order to push the boundaries of accuracy in models of the ancient economy and better test them, it is necessary to build up a stronger standard for systematically collected and adequately analysed data from urban sites of the ancient world.

Here we discuss which proxies could be derived for the archaeological site of Palmyra and their level of accuracy, based on the material from excavations, historic sources, and other sources. This oasis city, located in the Syrian steppe desert halfway between the Mediterranean and the Euphrates, flourished in the first three centuries AD (Raja 2021; Sartre-Fauriat and Sartre 2016; Sommer 2018). Its urban character, isolated location in the desert, easily delimited chronology, and rich history of research starting in the nineteenth century make it a good example of a typical archaeological site that could be used to investigate the relationship between economic growth and environmental degradation. Some of the peculiarities of the city need to be noted though, for example, its dependence on trade, which had an impact on the level of production-related activities and its location in a fairly inhospitable arid landscape limiting the agricultural potential of the hinterland. Palmyra has been explored archaeologically almost continuously since the late twentieth century when large expeditions to the Middle East undertook extensive archaeological research bringing to light entirely new Roman-period cities in the region (Raja 2018; Sartre-Fauriat 2019). Since then several archaeological missions have uncovered large parts of the city making Palmyra one of the most extensively studied archaeological sites in the world, even if not necessarily the best published one. Palmyra's history has been largely written on the basis of its grand monuments, the sculptural environment of the city, as well as the written sources (Yon 2002; Sartre 2005; Butcher 2003; Smith II 2013), which poses challenges to finding systematically collected datasets that could be used to derive economic and environmental indicators. However, it provides a good case study to reflect on the potential and challenges posed by the archaeological data.

Proxies for Economic Growth in Palmyra

Urban Growth

Given the focus of Palmyra excavations on its urban and funerary structures this is one of the most promising sources of proxy data. We know that the city grew extensively in the first centuries AD and at its largest extent covered about 120 ha, which situates it in the upper range of middle-sized cities, but not in the range of large cities, such as Rome and Antioch (Hanson 2016a, 769–70). Less is known about the domestic architecture of Palmyra, since archaeological fieldwork mainly has focused on the public and funerary monuments (Raja 2021, chapters 1 and 2). Nevertheless, numerous aspects of the city's fabric, such as urban evolution (Hammad 2010), the water system (Juchniewicz and Żuchowska 2012), or economic foundations of its prosperity (Matthews 1984), have been investigated and give us a relatively good understanding of its functioning.

Archaeological investigation has shown that the Hellenistic city occupied an area of around 20 ha to the south of the Roman city of Palmyra (Hammad 2010, 15–20; Schmidt-Colinet and al-As'ad 2013, 75). In the first century AD, we see the expansion of the city in the area to the north and east of the Hellenistic settlement (Hammad 2010, 21–34). Although this was the area of the Bronze Age settlement, there is little evidence that it was occupied during the Hellenistic period (Hammad 2010, 8–15). This phase in the city's development is characterized by the construction of sanctuaries, the main road network (Gawlikowski 2019), and a number of monumental structures, both public and private, such as multigenerational tower tombs (Henning 2013). It is difficult to trace the phases of the city's expansion between the first and the third centuries AD, but the construction of public and religious buildings continued well into the second century AD and in some cases until the fall of the city, which was brought about by Aurelian's two sacks of the city in AD 272 and 273 (Hammad 2010, 34–43; Gawlikowski 2019).

We can follow a broad-brush trajectory of Palmyra's urban growth to some extent, especially during the first and second centuries AD, at which time the city's layout changed dramatically. However, a detailed chrono-spatial mapping of the city would be required to make a more robust estimate of the changes in the occupied area.

Specialization

The urban nature of the site implies inherent specialization of its inhabitants. The transition from a largely pastoralist subsistence of the desert tribes to a large urban community necessarily implied specialization, as large parts of the population were not involved in food procurement.

Although no workshops have been excavated and published from Roman Palmyra, other archaeological data give rich insight into the fact that craft specialization thrived in the city. We see such specialization in the architecture of the city, urban as well as funerary — both basic building techniques but also decorational practices — including stone carving, wall painting, and bronzeworking (Raja and Steding 2021a; 2021b; Raja 2021; forthcoming). The numerous quarries around the city also bear witness to specialization in stone extraction (Schmidt-Colinet 1990; 1995). Individual objects found in Palmyra offer further evidence for specialization in workshops and craftsmanship, including jewellery (Mackay 1949; Raat 2013), textile production, including 'serialized production' of clothing from the second century AD (Schmidt-Colinet, Stauffer, and al-As'ad 2000, 92), and glass (Ployer 2013, 133).

Although the evidence for the existence of craft production in Palmyra is unequivocal, it remains difficult to trace its evolution or to date the intensification of craft specialization. Given the lack of excavated workshops, it would require a wide-ranging data collection focused on each craft product and its chronology. For example, cumulative probability graphs of different types of archaeological material have been used to trace how the city's production of funerary sculpture fluctuated over the centuries (Romanowska, Bobou, and Raja 2021; Raja, Bobou, and Romanowska forthcoming). Similar quantitative studies could be performed on other types of archaeological material.

Trade

While industry and agriculture were surely present in and around Palmyra, it is trade that characterized its economy (Seland 2018; 2016). The majority of Palmyra's development and prosperity has been linked to trade, placing it at the central node of the Roman East trade network (Hammad 2010, 1).The Tax Tariff from Palmyra dating to AD 137 gives detailed insight into local trade of foodstuffs coming from the agricultural hinterland around Palmyra (Shifman 2014). Despite the detail preserved in this document, it is limited to a singular moment in time in the second century AD limiting our ability to derive any temporal patterns from it.

Michał Gawlikowski (1994) and Michael Sommer (2018, Fig. 6.3) used epigraphic sources (thirty inscriptions mentioning caravans) to infer the intensity of long-distance trade (Parlasca 1992; Meyer, Seland, and Anfinset 2016; Seland 2016). Excavations have also provided ample evidence for long-distance trade (Schmidt-Colinet and al-As'ad 2013; Seland 2016) in the form of imported tableware pottery from Antioch and Athens and goods transported in Rhodian amphorae (Römer-Strehl 2013, 8–10). From 175 BC onwards, Parthian imports became the predominant imported pottery (Römer-Strehl 2013, 11–80). Pottery, being ubiquitous in archaeological contexts, is a primary source for reconstructing fluctuations and changes in the international trade of the city (Sommer 2018, 55–56).

Emphasis must be put on quantifying it to see to what degree it could reflect per-capita growth in the city. Once again household archaeology can give us a clue of what, beyond the luxury goods we already know of, was brought in from outside, and if the import of particular items (e.g. fine pottery) could have disincentivized local production. It is the consumption of most of society, not elites, that can really drive large-scale trade, and therefore evaluating it through households and refuse (in middens, sewers, etc.) is of crucial importance. For example, a campaign of synthesizing pottery data, currently dispersed in excavation reports and separate publications, could provide an insight into the fluctuating proportion of imported vs local wares. Other types of evidence could be quantified and analysed in a similar vein, such as glass and metal items and imported stones (i.e. Hirt 2021).

Investment in Capital Goods

The excavation focus on urban architecture means that we have a relatively good grasp of the infrastructure of Palmyra, especially in relation to water management. Water is and was precious in the region, and it was managed by the civic authorities. Palmyra was located at the Efqa Spring, which secured a perennial water supply. Other minor springs are also found near Palmyra, and there is evidence that rainwater also was managed extensively (Meyer, Seland, and Anfinset 2016; Meyer 2017). A system of cisterns was surveyed by Daniel Schlumberger (1951), and more recently a Norwegian-Syrian team revealed underground aqueducts (kanats) and other water management systems in the hinterland of Palmyra (Meyer 2017; Meyer, Seland, and Anfinset 2016). In the city, aqueducts and wells provided water through a network of pipes, channels, and sewers (Crouch 1975; Juchniewicz and Żuchowska 2012; Smith II 2013, 70–72; Meyer 2017). Manar Hammad (2010) connects the development of the city with the development of its water supply system.

Although the evidence for the existence of infrastructure is robust, it would require a better chronological framework to trace the evolution of the water system. It is also only indirectly related to economic activity given its vital function in sustaining the city population.

Proxies for Extensive Growth and Population Numbers

Population Size

Palmyra's population size has only been estimated very roughly. In 1999, for example, Eliodoro Savino (1999, 69–75), following Dora P. Crouch's argumentation (1972) but considering her numbers too high for a desert city, proposed that between 40,000 and 60,000 people lived in Palmyra in the second century AD, with 250,000 more based in the hinterland. Other estimations have been based on the size of the city combined with the size of the Palmyrene army mentioned in historical sources (Crouch 1972, but see Browning 1982, 43; Cameron 1969, 247–48). It is difficult to evaluate population size and its evolution beyond such sweeping statements as the observation that the city grew intensely in the first centuries AD after which its size stabilized until the unrest in the third century AD, followed by a sharp decline in urban population (Intagliata 2018, ix–x).

More extensive research aiming to calculate population growth and fluctuations based on the size of the urban core or the carrying capacity of the Palmyrene hinterland would be necessary to establish a baseline population curve for the city. In that regard, the use of remote-sensing techniques and targeted excavation could help us approximate household densities across different parts of the city, and small-scale prospection trenches can help us better establish the pattern of growth of the city, both in time and space. In this way, we could get a better understanding of the city's demography. Population data would also allow us to contextualize more general proxies for economic growth, like individual wealth. Studies on household wealth, and house sizes, would give us an insight into inequality. This would in turn allow us to understand the significance of elite wealth, for which we already have a substantial amount of data, and would help us gain a better picture of the overall state of the economy.

Individual and Public Wealth

The city was ornate with public and private displays of evergetism: sanctuaries (Kaizer 2002), monumental tombs (Henning 2013; Gawlikowski 1970), and other minor foundations, such as inscriptions and statues (Yon 2012; 2019), dot the urban landscape and its surroundings. In addition, the individual wealth of the Palmyrene elite is displayed in the commissioning of monuments for the funerary sphere, both tombs and portraits. Recent work has shown that the flows and fluctuations of the commissioning of the funerary sculpture match the overall economic development of the city (Romanowska, Bobou, and Raja 2021; Raja, Bobou, and Romanowska forthcoming).

Throughout the history of archaeological investigations in Palmyra, little emphasis has been given to domestic contexts limiting our ability to measure individual wealth through the distribution of luxurious objects and goods. Only over the last decades have archaeological missions begun to systematically publish small finds from their excavations (Schmidt-Colinet and al-As'ad 2013; Saito 2005; Higuchi and Izumi 1994; Higuchi and Saito 2001) meaning that, except for smaller areas of the city related to such excavations, we do not have comparable datasets. One exception being the corpus of the Palmyrene tesserae published in 1955 by Harald Ingholt, Henri Seyrig, and Jean Starcky. The tesserae were tokens allowing entry to religious banquets of the city, sponsored by members of the Palmyrene elite (Raja 2015; 2016).

To get a better picture of the economic dynamics of the city, a firmer focus on residential and industrial areas would be necessary. In that regard, the potential of household studies is enormous. Full quantification of the finds from Palmyra would allow for the evaluation of craft specialization as reflected by household commodities and the degree to which markets played a part in their allocation. Additionally, household commodities would also provide an insight into which everyday products were produced locally or imported. Besides houses, excavating industrial zones could eventually also uncover urban workshops bringing up data on the scale of production and the level of capital investment. Outside the city, more intensive survey and spot excavation of the rural sites would greatly help in characterizing rural settlement, and could potentially yield information regarding the intensification, the scale, and the specialization of rural production.

Environmental Proxies

Palmyra highlights another common issue with archaeological data. Any evaluation of the relationship between economic growth and environmental degradation necessitates data pertinent to both variables and collected at a comparable scale (e.g. the microregion). Even though the economic proxies in Palmyra are far from systematic, they provide a much stronger evidence base than the environmental indicators, which are virtually non-existent. Despite the early start to settlement survey in the hinterland of the city (Schlumberger 1951) it is only in recent years that a more systematic environmental reconstruction has been undertaken (Meyer, Seland, and Anfiset 2016; Meyer 2017; Seland 2016).

In terms of environmental proxies, the scope of insight that could be gained with environmental analysis in and around Palmyra is enormous. Geochemical analysis focused on the city's water systems could provide insight into potential contaminants in water, especially if compared with skeletal analysis of any surviving human remains to measure the impacts of environmental degradation on the ancient population. Further afield, coring and geochemical analysis could shed light on potential soil and water pollution. Also, chemical and pollen analyses of cores and geomorphological assessment with the aim of evaluating deforestation and soil erosion in the hills north of Palmyra could evaluate the sustainability of local food production and the impact of a rapidly growing urban population. The current gap in our knowledge can only be filled with modern analytical techniques, focused on measuring the changes to pollution levels, soil degradation and erosion, water quality and sustainability in Palmyra and the surrounding region. This problem — the availability of proxies for only one variable of the EKC model but not both — is likely to be a critical issue in this and many comparable cases.

Case Study Discussion

Palmyra showcases the difficulty related to deriving multiple economic and environmental proxies from one archaeological site. Despite its significance, isolated position in the Syrian Desert, and sustained research for many decades, systematic and comprehensive datasets are difficult to acquire. As with many similar sites, data coming from 'old' excavations pose particular difficulties as excavation techniques, analytical methods, and recording standards varied over time. However, what seems to be the main challenge currently is the limited amounts of quantified archaeological material and the focus on the monumental architecture of the city rather than household-level activity. This is not an uncommon issue at comparable sites but one that can be overcome with, undoubtedly substantial, research effort (e.g. Banerjea and others 2017).

The proxies for economic growth available in Palmyra leave a lot to be desired, at least for the specific purpose of measuring per-capita economic growth or decline. The overall urban development is poorly attested between the first and third centuries AD, i.e. during the city's heyday, which is the period most interesting for our purposes. Consequently, population calculations have only approximated the peak of population, and questions remain regarding the density of occupation in the city. Research has also focused on inscriptions, which allow us to track the pulse of private evergetism in the city. Tesserae have received scholarly attention, and if they represent elite spending on banquets for the public, they might add to the other proxies for elite wealth. Further quantification could also shed light on the scale of food distribution among the urban population, which would have important implications for the general economic output. More recently, the Palmyra Portrait Project (Krag and Raja 2019; Kropp and Raja 2014; Raja 2017) has created an extensive database of Palmyrene portraiture, which allows for statistical treatment of funerary portraits. The latter can provide evidence regarding population dynamics and the level of wealth of the elites. However, it will be difficult to extrapolate population-wide per-capita incomes and economic growth from these. Finally, despite the recent survey of the Palmyrena (Meyer 2009; 2011; 2013), which has provided a clearer picture of settlement in the hinterland, environmental datasets are virtually non-existent in the region. This leaves a substantial gap in our understanding of the subsistence base of the population and their environmental impact on the city's surroundings. In Palmyra, and more generally in the classical Near East, the traditional emphasis on monuments and fine art has resulted in limited information on the city's population beyond the elite and the environment in which they lived.

Discussion and Conclusions: The Role of Archaeology in Shaping Current Debates on the EKC Model

It is clear from this review that studies focused on reconstructing ancient economies are a rapidly expanding and highly dynamic field. Similarly, the waves of new analytical techniques for palaeoenvironmental reconstruction, from geochemical to biomarkers analyses, bring a wealth of information on a previously unprecedented scale. Interestingly, however, the two are rarely put together in a critical manner. Although few would deny that a general relationship between economic growth and human impact on the environment exists, the nature of this relationship remains elusive.

Although environmental degradation may look irreparable, even in the deep past human groups had tools at their disposal which would improve their environmental impact, such as soil management and construction of terraces to offset erosion. These measures require a high level of investment, sometimes necessitating the involvement of a whole community. The question is in what contexts past communities deemed it worthwhile to make such investments? Archaeological data could help us answer this type of question through elaboration of comparative case studies.

There are several caveats to this approach. For example, it is important to assess the 'visibility' of an environmental issue to past communities and their direct interest in dealing with it. It is not entirely clear in which cases the human impact on the environment was visible and understood by past people. While relating land clearance to centuries-long climate shifts was impossible for Neolithic farmers to recognize, other, more subtle impacts, such as the leaking of toxic pollutants from mining facilities that contaminate water and soil, could have been perceived through the health consequences to local populations. For example, written sources indicate that the concurrence of marshland, mosquitos, and malaria was well known to Romans. Furthermore, any potential actions to offset environmental damage, or the lack thereof, need to be considered within the wider social and cultural context of the community. Factors outside of an individual's control, such as resource availability, the geography of the region, social and organization structures, might enable or prevent the group from taking the necessary action. Sing C. Chew (2001) discusses at length the interdependent web of feedback loops between human ecology, environmental degradation, urbanization, and societal collapse using a range of case studies from Harappa to the Roman Empire and the Industrial Revolution. Such multi-proxy comparative approaches are becoming increasingly feasible thanks to new data and new techniques helping researchers to attack the problem from several fronts.

The spatio-temporal coherence of data remains difficult to achieve — where we have detailed environmental sequences may not be the same places as where equally detailed economic data is available. To test and falsify the EKC model necessitates both types of information, and they need to be closely aligned in terms of the chronological scale and geographical area. Comparing a year-on-year environmental sequence pertinent to a small region with decades- or centuries-long trends in the Roman economy is not meaningful, but seeing an increase in heavy metal contamination correlating with a mining boom in the region and a drop in life expectancy of local inhabitants could be highly informative. Pinpointing the causal interactions is another challenge. In both economic and environmental studies, unravelling the causality chains and determining which factors or the combinations thereof triggered observed shifts in societal-level behaviour is difficult even when deploying state-of-the-art computational techniques (Brughmans and others 2019; Romanowska and others 2021).

The case study presented here showcases the main challenges. Due to Palmyra's excavation history, we cannot use much of the standard archaeological evidence such as frequency of pottery types, presence of workshops, coinage, or material from the city's refuse dumps to gain an overall insight into its developmental patterns. What is needed are more systematically collected datasets showing changes to economic indicators over time and space. For example, the data gathered through the Palmyra Portrait Project demonstrates the utility of quantifying archaeological materials, even those usually associated with art history, such as funerary portraits, to assess the economic growth and decline of the city (Raja 2021). Such overarching work is time- and resource-consuming, but it has the potential to reveal trends in socio-natural systems that span centuries. In the future, a baseline of multiple case studies will serve as the basis for increasingly robust models of the ancient economy moving beyond anecdotal evidence and towards more systematic, qualitative, and analytically treated data, where both 'global'-scale data aggregations and individual 'microhistory' datasets have a role to play.

Here we propose a new framing for the highly dynamic branch of archaeological research including resilience studies, paleoecology, economic history, and ancient demography. While the EKC model may or may not be applicable to all past populations and types of environmental degradation it can serve as a lens to unite the efforts and provide a common theoretical framework for a wide range of specialists. Although it is interesting to know that the economy boomed or went bust in a specific time and place, or that a given community did not anticipate the damage to soil from clearing the trees, these microhistories can be used as 'data points' for more generalized conclusions. Ultimately, we are interested less in particularities of any one case study and more in the range of human responses to degrading environmental conditions. Under what circumstances were societies able to sacrifice resources and transform their behaviour to limit or offset their environmental impact? Have depopulation, abandonment, and societal collapse been the sole possible response to environmental degradation and can they be linked to economic growth? Do richer societies take more care of their surroundings and if so, why?

The most compelling pivot that links the study of longue-durée processes and trends in economy and human–environmental interactions are urban centres. Urban centres are the engine of the regional economy — of consumption, redistribution, production, and administration. The elevated level of population and its aggregated actions are also the main factor in environmental degradation (Grimm and others 2000). Finally, urban collapse is a dramatic and visible outcome of long-term processes, unsustainable strategies, and climate change that is easy to detect and measure in archaeological and historical records. Urban sites have for more than a century been a focus in archaeological research, but urban archaeology as a discipline has in fact only emerged after World War I (Raja and Sindbæk 2020a; 2020b; 2020c; Hass and Raja forthcoming). This new and exciting direction combining multidisciplinary strands of evidence could occupy a central place in urban archaeology. With the calls for a stronger establishment of palaeoenvironmental humanities (Hudson and others 2012; Hussain and Riede 2020; Ortman 2019) and the ongoing 'environmental turn' in many social and humanities sciences we are likely to see a growth in the amounts of palaeoenvironmental data. To simply look at them and conclude that societies interacted with their environment in, often, complex and unexpected ways is not enough. Stronger frameworks enabling cross-context comparison, testing of models, and the circumstances under which they do or do not work, investigating causality and mechanisms are all ambitions that can bring disciplines studying the past to the forefront of science concerned with modern challenges.

Abbreviations

Plin., *HN* Plinius maior, *Naturalis historia*.

Works Cited

Álvarez-Fernández, N., A. Martínez Cortizas, and O. López-Costas. 2020. 'Atmospheric Mercury Pollution Deciphered through Archaeological Bones', *Journal of Archaeological Science*, 119: 105159 <https://doi.org/10.1016/j.jas.2020.105159>.

Andel, T. H. van, E. Zangger, and A. Demitrack. 1990. 'Land Use and Soil Erosion in Prehistoric and Historical Greece', *Journal of Field Archaeology*, 17: 379–96 <https://doi.org/10.1179/009346990791548628>.

Andrieu-Ponel, V., P. Ponel, H. Bruneton, P. Leveau, and J.-L. de Beaulieu. 2000. 'Palaeoenvironments and Cultural Landscapes of the Last 2000 Years Reconstructed from Pollen and Coleopteran Records in the Lower Rhône Valley, Southern France', *The Holocene*, 10: 341–55.

Anselmetti, F. S., D. A. Hodell, D. Ariztegui, M. Brenner, and M. F. Rosenmeier. 2007. 'Quantification of Soil Erosion Rates Related to Ancient Maya Deforestation', *Geology*, 35: 915–18 <https://doi.org/10.1130/G23834A.1>.

Apergis, N. and I. Ozturk. 2015. 'Testing Environmental Kuznets Curve Hypothesis in Asian Countries', *Ecological Indicators*, 52: 16–22 <https://doi.org/10.1016/j.ecolind.2014.11.026>.

Arnold, P. J. 1991. 'Dimensional Standardization and Production Scale in Mesoamerican Ceramics', *Latin American Antiquity*, 2: 363–70.

Artzy, M. and D. Hillel. 1988. 'A Defense of the Theory of Progressive Soil Salinization in Ancient Southern Mesopotamia', *Geoarchaeology*, 3: 235–38 <https://doi.org/10.1002/gea.3340030306>.

Atack, J., F. Bateman, and R. A. Margo. 2008. 'Steam Power, Establishment Size, and Labor Productivity Growth in Nineteenth Century American Manufacturing', *Explorations in Economic History*, 45: 185–98.

Attema, P. 2017. 'Sedimentation as Geomorphological Bias and Indicator of Agricultural (Un)Sustainability in the Study of the Coastal Plains of South and Central Italy in Antiquity', *Journal of Archaeological Science: Reports*, 15: 459–69 <https://doi.org/10.1016/j.jasrep.2016.07.024>.

Bakker, J. T. 1999. *The Mills-Bakeries of Ostia: Description and Interpretation* (Amsterdam: Gieben).

Banerjea, R. Y., M. Badura, U. Kalējs, A. Cerina, K. Gos, S. Hamilton-Dyer, M. Maltby, K. Seetha, and A. Pluskowski. 2017. 'A Multi-Proxy, Diachronic and Spatial Perspective on the Urban Activities within an Indigenous Community in Medieval Riga, Latvia', *Quaternary International*, 460: 3–21.

Bang, P. F. 2008. *The Roman Bazaar: A Comparative Study of Trade and Markets in a Tributary Empire* (Cambridge: Cambridge University Press).

Baptista Neto, J. A., C. F. Barreto, C. G. Vilela, E. Monteiro da Fonseca, G. V. Melo, and O. M. Barth. 2017. 'Environmental Change in Guanabara Bay, SE Brazil, Based in Microfaunal, Pollen and Geochemical Proxies in Sedimentary Cores', *Ocean & Coastal Management*, 143, special issue, *The Challenge of Developing Policies and Management Strategies under Changing Baselines and Unbounded Boundaries*: 4–15 <https://doi.org/10.1016/j.ocecoaman.2016.04.010>.

Barker, G. 1995. *A Mediterranean Valley: Landscape Archaeology and 'Annales' History in the Biferno Valley* (London: Leicester University Press).

——. 2002. 'A Tale of Two Deserts: Contrasting Desertification Histories on Rome's Desert Frontiers', *World Archaeology*, 33: 488–507.

Barker, G., D. D. Gilbertson, J. Barri, and D. J. Mattingly (eds). 1996. *Farming the Desert: The UNESCO Libyan Valleys Archaeological Survey*, 2 vols (Tripoli: Department of Antiquities).

Bes, P. 2015. *Once upon a Time in the East: The Chronological and Geographical Distribution of Terra Sigillata and Red Slip Ware in the Roman East*, Roman and Late Antique Mediterranean Pottery, 6 (Oxford: Archaeopress).

Bindler, R., M.-L. Brännvall, I. Renberg, O. Emteryd, and H. Grip. 1999. 'Natural Lead Concentrations in Pristine Boreal Forest Soils and Past Pollution Trends: A Reference for Critical Load Models', *Environmental Science & Technology*, 33: 3362–67 <https://doi.org/10.1021/es9809307>.

Birch, T., V. Orfanou, A. Lichtenberger, R. Raja, G. Barfod, C. E. Lesher, I. Schulze, and W. Schulze. 2019. 'From *nummi minimi* to *fulūs* — Small Change and Wider Issues: Characterising Coinage from Gerasa/Jerash (Late Roman to Umayyad Periods)', *Archaeological and Anthropological Sciences*, 11: 5359–76.

Boserup, E. 1965. *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure* (London: Allen & Unwin).

Bowes, K. 2021. 'When Kuznets Went to Rome: Roman Economic Well-Being and the Reframing of Roman History', *Capitalism: A Journal of History and Economics*, 2: 7–40.

Bowman, A. and A. I. Wilson (eds). 2009. *Quantifying the Roman Economy: Methods and Problems*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press).

Bradley, R. 1982. 'The Destruction of Wealth in Later Prehistory', *Man*, 17: 108–22.

Browning, R. 1982. 'Biography', in W. V. Clausen and E. J. Kenney (eds), *The Cambridge History of Classical Literature* (Cambridge: Cambridge University Press), pp. 41–49.

Brughmans, T., J. W. Hanson, M. J. Mandich, I. Romanowska, X. Rubio-Campillo, S. Carrignon, S. Collins-Elliott, K. Crawford, D. Daems, F. Fulminante, T. de Haas, P. Kelly, M. del Carmen Moreno Escobar, E. Paliou, L. Prignano, and M. Ritondate. 2019. 'Formal Modelling Approaches to Complexity Science in Roman Studies: A Manifesto', *Theoretical Roman Archaeology Journal*, 2: 4 <https://doi.org/10.16995/traj.367>.

Bull, I. D., I. A. Simpson, P. F. van Bergen, and R. P. Evershed. 1999. 'Muck 'n' Molecules: Organic Geochemical Methods for Detecting Ancient Manuring', *Antiquity*, 73.279: 86–96.

Butcher, K. 2003. *Roman Syria and the Near East* (London: British Museum).

Cameron, A. 1969. 'Theodosius the Great and the Regency of Stilicho', *Harvard Studies in Classical Philology*, 73: 247–80.

Canti, M. and D. J. Huisman. 2015. 'Scientific Advances in Geoarchaeology during the Last Twenty Years', *Journal of Archaeological Science*, 56, special issue, *Scoping the Future of Archaeological Science: Papers in Honour of Richard Klein*: 96–108 <https://doi.org/10.1016/j.jas.2015.02.024>.

Cappers, R. T. J. 2006. *Roman Foodprints at Berenike: Archaeobotanical Evidence of Subsistence and Trade in the Eastern Desert of Egypt* (Los Angeles: Cotsen Institute of Archaeology).

Carandini, A. 1983. 'Pottery and the African Economy', in P. Garnsey, K. Hopkins, and C. R. Whittaker (eds), *Trade in the Ancient Economy* (Berkeley: University of California Press), pp. 145–62.

Carreras, C. 1998. 'Britannia and the Imports of Baetican and Lusitanian Amphorae', *Journal of Iberian Archaeology*, 1998: 159–72.

Carreras, C. and P. De Soto. 2013. 'The Roman Transport Network: A Precedent for the Integration of the European Mobility', *Historical Methods: A Journal of Quantitative and Interdisciplinary History*, 46.3: 117–33.

Carreras, C., A. López Mullor, and J. Guitart. 2013. 'El Baix Llobregat: una vall vinícola i terrissera de l'ager Barcinonensis', in C. Carreras, A. López Mullor, and J. Guitart (eds), *Barcino*, II: *Marques i terrisseries d'àmfores al Baix Llobregat*, Corpus international des timbres amphoriques, 18 (Barcelona: Institut d'Estudis Catalans), pp. 11–16.

Cattaneo, A., Y. Couillard, S. Wunsam, and M. Courcelles. 2004. 'Diatom Taxonomic and Morphological Changes as Indicators of Metal Pollution and Recovery in Lac Dufault (Québec, Canada)', *Journal of Paleolimnology*, 32: 163–75 <https://doi.org/10.1023/B:JOPL.0000029430.78278.a5>.

Chamberlain, A. 2006. *Demography in Archaeology* (Cambridge: Cambridge University Press).

Chaney, T. and R. Ossa. 2013. 'Market Size, Division of Labor, and Firm Productivity', *Journal of International Economics*, 90: 177–80.

Chew, S. C. 2001. *World Ecological Degradation: Accumulation, Urbanization, and Deforestation, 3000 B.C.–A.D. 2000* (Lanham: AltaMira).

Cleaver, T. 2014. *Economics: The Basics*, 3rd edn (London: Routledge).

Cooke, C. A., P. H. Balcom, H. Biester, and A. P. Wolfe. 2009. 'Over Three Millennia of Mercury Pollution in the Peruvian Andes', *Proceedings of the National Academy of Sciences of the United States of America*, 106: 8830–34 <https://doi.org/10.1073/pnas.0900517106>.

Cooke, C. A., A. Martínez-Cortizas, R. Bindler, and M. Sexauer Gustin. 2020. 'Environmental Archives of Atmospheric Hg Deposition: A Review', *Science of the Total Environment*, 709: 134800 <https://doi.org/10.1016/j.scitotenv.2019.134800>.

Crawford, M. H. 1969. 'Coin Hoards and the Pattern of Violence in the Late Republic', *Papers of the British School at Rome*, 37: 76–81.

Crouch, D. 1972. 'A Note on the Population and Area of Palmyra', *Mélanges de l'Université Saint-Joseph*, 47: 241–50.

——. 1975. 'The Water System of Palmyra', *Studia Palmyreńskie*, 6–7: 151–86.

Curtis, J. H., M. Brenner, D. A. Hodell, R. A. Balser, G. A. Islebe, and H. Hooghiemstra. 1998. 'A Multi-Proxy Study of Holocene Environmental Change in the Maya Lowlands of Peten, Guatemala', *Journal of Paleolimnology*, 19: 139–59 <https://doi.org/10.1023/A:1007968508262>.

Davies, M. I. J. 2015. 'Economic Specialisation, Resource Variability, and the Origins of Intensive Agriculture in Eastern Africa', *Rural Landscapes: Society, Environment, History*, 2: 1–18.

Deevey, E. S., D. S. Rice, P. M. Rice, H. H. Vaughan, M. Brenner, and S. Flannery. 1979. 'Mayan Urbanism: Impact on a Tropical Karst Environment', *Science*, 206.4416: 298–306 <https://doi.org/10.1126/science.206.4416.298>.

Devault, A. M., K. McLoughlin, C. Jaing, S. Gardner, T. M. Porter, J. M. Enk, J. Thissen, J. Allen, M. Borucki, S. N. DeWitte, A. N. Dhody, and H. N. Poinar. 2014. 'Ancient Pathogen DNA in Archaeological Samples Detected with a Microbial Detection Array', *Scientific Reports*, 4: 4245 <https://doi.org/10.1038/srep04245>.

De Vito, C., L. Medeghini, S. Mignardi, D. Orlandi, L. Nigro, F. Spagnoli, P. P. Lottici, and D. Bersani. 2014. 'Technological Fingerprints of Black-Gloss Ware from Motya (Western Sicily, Italy)', *Applied Clay Science*, 88–89: 202–13.

De Vos, M. 2013. 'The Rural Landscape of Thugga: Farms, Presses, Mills and Transport', in A. Bowman and A. I. Wilson (eds), *The Roman Agricultural Economy: Organization, Investment, and Production*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 143–218.

Dinda, S. 2004. 'Environmental Kuznets Curve Hypothesis: A Survey', *Ecological Economics*, 49: 431–55 <https://doi.org/10.1016/j.ecolecon.2004.02.011>.

——. 2005. 'A Theoretical Basis for the Environmental Kuznets Curve', *Ecological Economics*, 53: 403–13 <https://doi.org/10.1016/j.ecolecon.2004.10.007>.

Ethier, W. J. 2009. 'Economies of Scale', in K. A. Reinert, R. S. Rajan, A. J. Glass, and L. S. Davis (eds), *The Princeton Encyclopedia of the World Economy*, I (Princeton: Princeton University Press), pp. 332–37.

Fafchamps, M. and F. Shilpi. 2005. 'Cities and Specialisation: Evidence from South Asia', *The Economic Journal*, 115.503: 477–504.

Fentress, E. 2009. 'Peopling the Countryside: Roman Demography in the Albegna Valley and Jerba', in A. Bowman and A. I. Wilson (eds), *Quantifying the Roman Economy: Methods and Problems*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 127–74.

Fentress, E., A. Drine, R. Holod, and A. A. Kaci. 2009. *An Island through Time: Jerba Studies*, Journal of Roman Archaeology, Supplementary Series, 71 (Portsmouth, RI: Journal of Roman Archaeology).

Fishman, A. and A. Simhon. 2002. 'The Division of Labor, Inequality and Growth', *Journal of Economic Growth*, 7: 117–36.

Flohr, M. 2013. *The World of the Fullo: Work, Economy, and Society in Roman Italy*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press).

——. 2017. 'Quantifying Pompeii: Population, Inequality, and the Urban Economy', in A. I. Wilson and M. Flohr (eds), *The Economy of Pompeii*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 53–86.

French, J. C., P. Riris, J. Fernandéz-López de Pablo, S. Lozano, and F. Silva. 2021. 'A Manifesto for Palaeodemography in the Twenty-First Century', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 376.1816: 20190707 <https://doi.org/10.1098/rstb.2019.0707>.

Gawlikowski, M. 1970. *Monuments funéraires de Palmyre*, Travaux du Centre d'archéologie méditerranéenne de l'Académie polonaise des sciences, 9 (Warsaw: PWN).

——. 1994. 'Palmyra as a Trading Centre', *Iraq*, 56: 27 <https://doi.org/10.2307/4200382>.

——. 2019. 'The Making of a City', in A.-M. Nielsen and R. Raja (eds), *The Road to Palmyra* (Copenhagen: Ny Carlsberg Glyptotek), pp. 77–91.

Grimm, N. B., J. Grove Grove, S. T. A. Pickett, and C. L. Redman. 2000. 'Integrated Approaches to Long-Term Studies of Urban Ecological Systems: Urban Ecological Systems Present Multiple Challenges to Ecologists: Pervasive Human Impact and Extreme Heterogeneity of Cities, and the Need to Integrate Social and Ecological Approaches, Concepts, and Theory', *BioScience*, 50: 571–84 <https://doi.org/10.1641/0006-3568(2000)050[0571:IATLTO]2.0.CO;2>.

Grove, A. T. and O. Rackham. 2003. *The Nature of Mediterranean Europe: An Ecological History* (New Haven: Yale University Press).

Hammad, M. 2010. *Palmyre: transformations urbaines; développement d'une ville antique de la marge aride syrienne*, Librairie de l'architecture et de la Ville (Paris: Geuthner).

Hanson, J. W. 2016a. *An Urban Geography of the Roman World, 100 BC to AD 300*, Archaeopress Roman Archaeology, 18 (Oxford: Archaeopress).

——. 2016b. 'Cities Database (OXREP Databases) Version 1.0' <http://oxrep.classics.ox.ac.uk/databases/cities/> [accessed 24 November 2020]; <https://doi.org/10.5287/bodleian:eqapevAn8>.

Hanson, J. W. and S. G. Ortman. 2017. 'A Systematic Method for Estimating the Populations of Greek and Roman Settlements', *Journal of Roman Archaeology*, 30: 301–24.

Hanson, J. W., S. G. Ortman, and J. Lobo. 2017. 'Urbanism and the Division of Labour in the Roman Empire', *Journal of the Royal Society Interface*, 14.136 <https://doi.org/10.1098/rsif.2017.0367>.

Harbaugh, W. T., A. Levinson, and D. M. Wilson. 2002. 'Reexamining the Empirical Evidence for an Environmental Kuznets Curve', *The Review of Economics and Statistics*, 84: 541–51 <https://doi.org/10.1162/003465302320259538>.

Harper, K. 2016. 'People, Plagues, and Prices in the Roman World: The Evidence from Egypt', *The Journal of Economic History*, 76: 803–39.

Hass, T. A. and R. Raja. Forthcoming. 'Julius Caesar and the Forum Caesaris: World History, Historiography and Reception Investigated through Caesar Biographies by Danish Writers of the Early Twentieth Century', *The International Journal of Classical Tradition*.

Henning, A. 2013. *Die Turmgräber von Palmyra: Eine locale Bauform im kaizerzeitlichen Syrien als Ausdruck kultureller Identität*, Orient-Archäologie, 29 (Rahden: Leidorf).

Higuchi, T. and T. Izumi. 1994. *Tombs A and C, Southeast Necropolis, Palmyra, Syria: Surveyed in 1990–92*, Publication of Research Center for Silk Roadology, 1 (Nara: Research Center for Silk Roadology).

Higuchi, T. and K. Saito. 2001. *Tomb F: Tomb of BWLH and BWRP; Southeast Necropolis, Palmyra, Syria*, Publication of Research Center for Silk Roadology, 2 (Nara: Research Center for Silk Roadology).

Hirt, A. M. 2021. 'Palmyra, Syria, and "Imperial" Marble', in R. Raja and J. Steding (eds), *Production Economy in Greater Roman Syria: Trade Networks and Production Processes*, Studies in Palmyrene Archaeology and History, 2 (Turnhout: Brepols), pp. 101–22.

Hirth, K. G. 1998. 'The Distributional Approach: A New Way to Identify Marketplace Exchange in the Archaeological Record', *Current Anthropology*, 39: 451–76.

Hobson, M. S. 2014. 'A Historiography of the Study of the Roman Economy: Economic Growth, Development, and Neoliberalism', in H. Platts, J. Pierce, C. Barron, J. Lundock, and J. Yoo (eds), *TRAC 2013: Proceedings of the Twenty-Third Annual Theoretical Roman Archaeology Conference, King's College, London 2013* (Oxford: Oxbow), pp. 11–26.

Holdridge, G., S. M. Kristiansen, A. Lichtenberger, R. Raja, and I. A. Simpson. 2017. 'City and Wadi: Exploring the Environs of Jerash', *Antiquity*, 91.358, Antiquity Project Gallery: E7 <https://doi.org/10.15184/aqy.2017.123>.

Hong Sungmin, J.-P. Candelone, C. C. Patterson, and C. F. Boutron. 1996. 'History of Ancient Copper Smelting Pollution during Roman and Medieval Times Recorded in Greenland Ice', *Science*, 272.5259: 246–49 <https://doi.org/10.1126/science.272.5259.246>.

Howgego, C. 2013. 'The Monetization of Temperate Europe', *Journal of Roman Studies*, 103: 16–45.

Hudson, M. J., M. Aoyama, K. C. Hoover, and J. Uchiyama. 2012. 'Prospects and Challenges for an Archaeology of Global Climate Change', *WIREs Climate Change*, 3.4: 313–28 <https://doi.org/10.1002/wcc.174>.

Hudson-Edwards, K. A. 2018. 'Water Pollution', in S. L. Lopéz Varela (ed.), *The Encyclopedia of Archaeological Sciences* (Malden: Wiley-Blackwell), pp. 1–3 <https://doi.org/10.1002/9781119188230.saseas0606>.

Hunt, C. O. 1997. 'Quaternary Deposits in the Maltese Islands: A Microcosm of Environmental Change in Mediterranean Lands', *GeoJournal*, 41.2: 101–09 <https://doi.org/10.1023/A:1006824605544>.

Hussain, S. T. and F. Riede. 2020. 'Paleoenvironmental Humanities: Challenges and Prospects of Writing Deep Environmental Histories', *WIREs Climate Change*, 11.5: e667 <https://doi.org/10.1002/wcc.667>.

Ingholt, H., H. Seyrig, and J. Starcky. 1955. *Recueil des Tessères de Palmyre* (Paris: Geuthner).

Intagliata, E. E. 2018. *Palmyra after Zenobia AD 273–750: An Archaeological and Historical Reappraisal* (Oxford: Oxbow).

Jackson, L. F. 1984. 'Hierarchic Demand and the Engel Curve for Variety', *The Review of Economics and Statistics*, 66: 8–15.

James, P. A., C. B. Mee, and G. J. Taylor. 1994. 'Soil Erosion and the Archaeological Landscape of Methana, Greece', *Journal of Field Archaeology*, 21: 395–416 <https://doi.org/10.1179/009346994797175523>.

Juchniewicz, K. and M. Żuchowska. 2012. 'Water Supply in Palmyra, a Chronological Approach', in M. Żuchowska (ed.), *The Archaeology of Water Supply*, British Archaeological Reports, International Series, 2414 (Oxford: Archaeopress), pp. 61–73 <https://www.researchgate.net/publication/265726045_Water_Supply_in_Palmyra_a_Chronological_Approach> [accessed 23 September 2020].

Kaizer, T. 2002. *The Religious Life of Palmyra: A Study of the Social Patterns of Worship in the Roman Period* (Stuttgart: Steiner).

Kakoulli, I., S. V. Prikhodko, C. Fischer, M. Cilluffo, M. Uribe, H. A. Brechtel, S. C. Fakra, and M. A. Marcus. 2014. 'Distribution and Chemical Speciation of Arsenic in Ancient Human Hair Using Synchrotron Radiation', *Analytical Chemistry*, 86: 521–26 <https://doi.org/10.1021/ac4024439>.

Kandulu, J. M., B. A. Bryan, D. King, and J. D. Connor. 2012. 'Mitigating Economic Risk from Climate Variability in Rain-Fed Agriculture through Enterprise Mix Diversification', *Ecological Economics*, 79: 105–12.

Kaplan, J. O., K. M. Krumhardt, and N. Zimmermann. 2009. 'The Prehistoric and Preindustrial Deforestation of Europe', *Quaternary Science Reviews*, 28: 3016–34 <https://doi.org/10.1016/j.quascirev.2009.09.028>.

Krag, S. and R. Raja. 2019. *Women, Children and the Family in Palmyra*, Palmyrene Studies, 3, Scientia Danica, Series H, Humanistica, 4, 10 (Copenhagen: The Royal Danish Academy of Sciences and Letters).

Kropp, A. J. M. and R. Raja. 2014. 'The Palmyra Portrait Project', *Syria: archéologie, art et histoire*, 91: 393–408.

Krugman, P. R. 1979. 'Increasing Returns, Monopolistic Competition, and International Trade', *Journal of International Economics*, 9: 469–79.

Kuckuck, J. 2014. 'Testing Wagner's Law at Different Stages of Economic Development', *Finanzarchiv/Public Finance Analysis*, 70: 128–68.

Kuznets, S. 1955. 'Economic Growth and Income Inequality', *The American Economic Review*, 45: 1–28.

Lagerås, P. 2014. 'Medieval Colonisation and Abandonment in the South Swedish Uplands: A Review of Settlement and Land Use Dynamics Inferred from the Pollen Record', *Archaeologia Baltica*, 20: 77–90.

Langdon, S. 2005. 'Views of Wealth, a Wealth of Views: Grave Goods in Iron Age Attica', in D. Lyons and R. Westbrook (eds), *Women and Property in Ancient Near Eastern and Mediterranean Societies* (Cambridge, MA: Center for Hellenic Studies, Harvard University), pp. 229–48.

Lentz, D. L., T. L. Hamilton, N. P. Dunning, V. L. Scarborough, T. P. Luxton, A. Vonderheide, E. J. Tepe, C. J. Perfetta, J. Brunemann, L. Grazioso, F. Valdez, K. B. Tankersley, and A. A. Weiss. 2020. 'Molecular Genetic and Geochemical

Assays Reveal Severe Contamination of Drinking Water Reservoirs at the Ancient Maya City of Tikal', *Scientific Reports*, 10: 10316 <https://doi.org/10.1038/s41598-020-67044-z>.

Leveau, P. 1996. 'The Barbegal Water Mill in its Environment: Archaeology and the Economic and Social History of Antiquity', *Journal of Roman Archaeology*, 9: 137–53.

Lichtenberger, A., R. Raja, E. H. Seland, T. Kinnaird, and I. A. Simpson. 2019. 'Urban–Riverine Hinterland Synergies in Semi-Arid Environments: Millennial-Scale Change, Adaptations, and Environmental Responses at Gerasa/Jerash', *Journal of Field Archaeology*, 44: 333–51 <https://doi.org/10.1080/00934690.2019.1625619>.

Lichtenberger, A., R. Raja, E. H. Seland, and I. A. Simpson. 2021. 'Scaling up and Zooming in: Global History and High Definition Archaeology Perspectives on the Longue Durée of Urban–Environmental Relations in Gerasa (Jerash, Jordan)', *Journal of Global History*, 2021: 1–20 <https://doi.org/10.1017/S1740022821000012>.

Liu Jinyu. 2013. 'Professional Associations', in P. Erdkamp (ed.), *The Cambridge Companion to Ancient Rome* (Cambridge: Cambridge University Press), pp. 352–68.

Lo Cascio, E. 2009. 'Urbanization as a Proxy of Demographic and Economic Growth', in A. Bowman and A. I. Wilson (eds), *Quantifying the Roman Economy: Methods and Problems*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 87–106.

Long, L. E. 2017. 'Extracting Economics from Roman Marble Quarries', *The Economic History Review*, 70: 52–78.

López-Costas, O., M. Kylander, N. Mattielli, N. Álvarez-Fernández, M. Pérez-Rodríguez, T. Mighall, R. Bindler, and A. Martínez Cortizas. 2020. 'Human Bones Tell the Story of Atmospheric Mercury and Lead Exposure at the Edge of Roman World', *Science of the Total Environment*, 710: 136319 <https://doi.org/10.1016/j.scitotenv.2019.136319>.

Luzzadder-Beach, S. 2000. 'Water Resources of the Chunchucmil Maya', *Geographical Review*, 90: 493 <https://doi.org/10.2307/3250781>.

Mackay, D. 1949. 'The Jewellery of Palmyra and its Significance', *Iraq*, 11.2: 160–87.

Magnani, E. 2000. 'The Environmental Kuznets Curve, Environmental Protection Policy and Income Distribution', *Ecological Economics*, 32: 431–43 <https://doi.org/10.1016/S0921-8009(99)00115-9>.

Malouta, M. and A. I. Wilson. 2013. 'Mechanical Irrigation: Water-Lifting Devices in the Archaeological Evidence and in the Egyptian Papyri', in A. Bowman and A. I. Wilson (eds), *The Roman Agricultural Economy: Organization, Investment, and Production*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 273–305.

Manuel, M., D. Lightfoot, and M. Fattahi. 2018. 'The Sustainability of Ancient Water Control Techniques in Iran: An Overview', *Water History*, 10: 13–30 <https://doi.org/10.1007/s12685-017-0200-7>.

Marston, J. M. 2011. 'Archaeological Markers of Agricultural Risk Management', *Journal of Anthropological Archaeology*, 30: 190–205.

Martínez Cortizas, A., E. García-Rodeja, X. Pontevedra Pombal, J. C. Nóvoa Muñoz, D. Weiss, and A. Cheburkin. 2002. 'Atmospheric Pb Deposition in Spain during the Last 4600 Years Recorded by Two Ombrotrophic Peat Bogs and Implications for the Use of Peat as Archive', *Science of the Total Environment*, 292.1, special issue, *Peat Bog Archives of Atmospheric Metal Deposition*: 33–44 <https://doi.org/10.1016/S0048-9697(02)00031-1>.

Martínez-Cortizas, A., X. Pontevedra-Pombal, E. García-Rodeja, J. C. Nóvoa-Muñoz, and W. Shotyk. 1999. 'Mercury in a Spanish Peat Bog: Archive of Climate Change and Atmospheric Metal Deposition', *Science*, 284.5416: 939–42 <https://doi.org/10.1126/science.284.5416.939>.

Martínez Cortizas, A., X. Pontevedra Pombal, J. C. Nóvoa Muñoz, and E. García-Rodeja. 2000. 'Turberas de montaña del Noroeste de la Península Ibérica', *Edafología*, 7: 1–29.

Marzano, A. 2007. *Roman Villas in Central Italy: A Social and Economic History* (Leiden: Brill).

——. 2013a. 'Agricultural Production in the Hinterland of Rome: Wine and Olive Oil', in A. Bowman and A. I. Wilson (eds), *The Roman Agricultural Economy: Organization, Investment, and Production*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 85–106.

——. 2013b. 'Capital Investment and Agriculture: Multi-Press Facilities from Gaul, the Iberian Peninsula, and the Black Sea Region', in A. Bowman and A. I. Wilson (eds), *The Roman Agricultural Economy: Organization, Investment, and Production*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 107–41.

Matthews, J. F. 1984. 'The Tax Law of Palmyra: Evidence for Economic History in a City of the Roman East', *Journal of Roman Studies*, 74: 157–80.

Mattingly, D. J. 2009. 'Peopling Ancient Landscapes: Potential and Problems', in A. Bowman and A. I. Wilson (eds), *Quantifying the Roman Economy: Methods and Problems*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 163–74 <https://doi.org/10.1093/acprof:oso/9780199562596.003.006>.

McConnell, J. R., A. I. Wilson, A. Stohl, M. M. Arienzo, N. J. Chellman, S. Eckhardt, E. M. Thompson, A. M. Pollard, and J. P. Steffensen. 2018. 'Lead Pollution Recorded in Greenland Ice Indicates European Emissions Tracked Plagues, Wars, and Imperial Expansion during Antiquity', *Proceedings of the National Academy of Sciences of the United States of America*, 115: 5726–31.

McCool, J.-P. P., S. G. Fladd, V. L. Scarborough, S. Plog, N. P. Dunning, L. A. Owen, A. S. Watson, K. J. Bishop, B. E. Crowley, E. A. Haussner, K. B. Tankersley, D. Lentz, C. Carr, and J. L. Thress. 2018. 'Soil Analysis in Discussions of Agricultural Feasibility for Ancient Civilizations: A Critical Review and Reanalysis of the Data and Debate from Chaco Canyon, New Mexico', *PLoS ONE*, 13.6: e0198290 <https://doi.org/10.1371/journal.pone.0198290>.

McNeil, C. L., D. A. Burney, and L. P. Burney. 2010. 'Evidence Disputing Deforestation as the Cause for the Collapse of the Ancient Maya Polity of Copan, Honduras', *Proceedings of the National Academy of Sciences of the United States of America*, 107: 1017–22 <https://doi.org/10.1073/pnas.0904760107>.

McWethy, D., C. Whitlock, J. Wilmshurst, M. Mcglone, and Xun Li. 2009. 'Rapid Deforestation of South Island, New Zealand, by Early Polynesian Fires', *Holocene*, 19: 883–97 <https://doi.org/10.1177/0959683609336563>.

Meyer, J. C. 2009. 'Palmyrena: Palmyra and the Surrounding Territory. Joint Syrian-Norwegian Project. Surface Survey North of Palmyra, April and May 2009. Preliminary Report, Historical Period', report published online at <https://hdl.handle.net/1956/10471> [accessed 22 March 2021].

——. 2011. 'Palmyrena: Palmyra and the Surrounding Territory. Joint Syrian-Norwegian Project. Surface Survey North of Palmyra, Jebel Merah, April and May 2011. Report. Historical Period', report published online at <https://hdl.handle.net/1956/10474> [accessed 22 March 2021].

——. 2013. 'City and Hinterland: Villages and Estates North of Palmyra. New Perspectives', *Studia Palmyreńskie*, 12: 269–86.

——. 2017. *Palmyrena: Palmyra and the Surrounding Territory from the Roman to the Early Islamic Period* (Oxford: Archaeopress).

Meyer, J. C., E. E. Seland, and N. Anfinset (eds). 2016. *Palmyrena: City, Hinterland and Caravan Trade between Orient and Occident; Proceedings of the Conference Held in Athens, December 1–3, 2012* (Oxford: Archaeopress).

Middleton, G. D. 2012. 'Nothing Lasts Forever: Environmental Discourses on the Collapse of Past Societies', *Journal of Archaeological Research*, 20: 257–307.

Mikesell, M. W. 1969. 'The Deforestation of Mount Lebanon', *Geographical Review*, 59: 1–28 <https://doi.org/10.2307/213080>.

Milanovic, B., P. H. Lindert, and J. G Williamson. 2007. 'Measuring Ancient Inequality', *National Bureau of Economic Research Working Paper Series*, October 2007: working paper 13550 <https://doi.org/10.3386/w13550>.

Miller, N. 1985. 'Paleoethnobotanical Evidence for Deforestation in Ancient Iran: A Case Study of Urban Malyan', *Journal of Ethnobiology*, 5: 1–19.

Mitchell, P. D., E. Stern, and Y. Tepper. 2008. 'Dysentery in the Crusader Kingdom of Jerusalem: An ELISA Analysis of Two Medieval Latrines in the City of Acre (Israel)', *Journal of Archaeological Science*, 35: 1849–53 <https://doi.org/10.1016/j.jas.2007.11.017>.

Morgan, C. 2015. 'Is It Intensification Yet? Current Archaeological Perspectives on the Evolution of Hunter-Gatherer Economies', *Journal of Archaeological Research*, 23: 163–213.

Morris, I. 2005. 'Archaeology, Standards of Living, and Greek Economic History', in J. G. Manning and I. Morris (eds), *The Ancient Economy: Evidence and Models* (Stanford: Stanford University Press), pp. 91–126.

Morrison, K. D. 1994. 'The Intensification of Production: Archaeological Approaches', *Journal of Archaeological Method and Theory*, 1: 111–59.

Murphy, E. A. 2017. 'Roman Workers and their Workplaces: Some Archaeological Thoughts on the Organization of Workshop Labour in Ceramic Production', in K. S. Verboven and C. Laes (eds), *Work, Labour, and Professions in the Roman World* (Leiden: Brill), pp. 133–46.

Murphy, E. A. and J. Poblome. 2016. 'A Late Antique Ceramic Workshop Complex: Evidence for Workshop Organisation at Sagalassos (Southwest Turkey)', *Anatolian Studies*, 66: 185–99.

——. 2020. 'Intramuros: Investigating Relations between Cross-Industry Practices and Networks through Sixth Century AD Sagalassos', *Journal of Urban Archaeology*, 3: 101–15.

Oonk, S., C. P. Slomp, and D. J. Huisman. 2009. 'Geochemistry as an Aid in Archaeological Prospection and Site Interpretation: Current Issues and Research Directions', *Archaeological Prospection*, 16: 35–51 <https://doi.org/10.1002/arp.344>.

Oonk, S., C. P. Slomp, D. J. Huisman, and S. P. Vriend. 2009. 'Geochemical and Mineralogical Investigation of Domestic Archaeological Soil Features at the Tiel-Passewaaij Site, the Netherlands', *Journal of Geochemical Exploration*, 101.2: 155–65 <https://doi.org/10.1016/j.gexplo.2008.06.004>.

Orejas, A. and F. J. Sánchez-Palencia. 2002. 'Mines, Territorial Organization, and Social Structure in Roman Iberia: Carthago Noua and the Peninsular Northwest', *American Journal of Archaeology*, 106: 581–99.

Ortman, S. G. 2019. 'A New Kind of Relevance for Archaeology', *Frontiers in Digital Humanities*, 6: 16 <https://doi.org/10.3389/fdigh.2019.00016>.

Ortman, S. and J. Lobo. 2020. 'Smithian Growth in a Nonindustrial Society', *Science Advances*, 6.25: eaba5694.

Palmisano, A., A. Bevan, and S. Shennan. 2017. 'Comparing Archaeological Proxies for Long-Term Population Patterns: An Example from Central Italy', *Journal of Archaeological Science*, 87: 59–72.

Parker, A. J. 1992. *Ancient Shipwrecks of the Mediterranean & the Roman Provinces*, British Archaeological Reports, International Series, 580 (Oxford: British Archaeological Reports).

Parlasca, K. 1992. 'Auswärtige Beziehungen Palmyras im Lichte archäologischer Funde', *Damaszener Mitteilungen*, 6: 257–65.

Peña, J. T. 2007. *Roman Pottery in the Archaeological Record* (Cambridge: Cambridge University Press).

Ployer, R. 2013. 'Gläser', in A. Schmidt-Colinet and K. al-As'ad (eds), *Palmyras Reichtum durch weltweiten Handel: Archäologische Untersuchungen im Bereich der hellenistischen Stadt*, II: *Kleinfunde* (Vienna: Holzhausen), pp. 127–205.

Pongratz, J., C. Reick, T. Raddatz, and M. Claussen. 2008. 'A Reconstruction of Global Agricultural Areas and Land Cover for the Last Millennium', *Global Biogeochemical Cycles*, 22.3 <https://doi.org/10.1029/2007GB003153>.

Prodromidis, P. I. 2009. 'Economic Environment, Policies and Inflation in the Roman Empire up to Diocletian's Price Edict', *The Journal of European Economic History*, 38: 567.

Raat, A. 2013. 'Diadems: A Girl's Best Friend? Jewellery Finds and Sculptural Representations of Jewellery from Rome and Palmyra in the First Two Centuries AD' (unpublished master's thesis, Leiden University) <https://studenttheses.universiteitleiden.nl/access/item%3A2658944/view> [accessed 4 May 2021].

Raja, R. 2015. 'Cultic Dining and Religious Patterns in Palmyra: The Case of the Palmyrene Banqueting Tesserae', in S. Faust, M. Seifert, and L. Ziemer (eds), *Antike. Architektur. Geschichte: Festschrift für Inge Nielsen zum 65. Geburtstag* (Aachen: Shaker), pp. 181–200.

——. 2016. 'In and out of Contexts: Explaining Religious Complexity through the Banqueting Tesserae from Palmyra', *Religion in the Roman Empire*, 2: 340–71.

——. 2017. 'Powerful Images of the Deceased: Palmyrene Funerary Portrait Culture between Local, Greek and Roman Representations', in D. Boschung and F. Queyrel (eds), *Bilder der Macht: Das griechische Porträt und seine Verwendung in der antiken Welt* (Paderborn: Fink), pp. 319–48.

——. 2018. 'Palmyrene Funerary Portraits, Collection Histories and Current Research', in J. Aruz (ed.), *Palmyra: Mirage in the Desert* (New York: Metropolitan Museum), pp. 100–09.

——. 2021. *Pearl of the Desert: A History of Palmyra* (Oxford: Oxford University Press).

——. Forthcoming. 'Populating Public Palmyra', in C. P. Dickenson (ed.), *Public Statues across Time and Cultures* (Routledge: London).

Raja, R., O. Bobou, and I. Romanowska. Forthcoming. 'Three Hundred Years of Palmyrene History: Unlocking Archaeological Data for Studying Past Societal Transformations', *PloS ONE*.

Raja, R. and S. M. Sindbæk. 2020. 'Biographies of Place: An Introduction', *Journal of Urban Archaeology*, 2: 11–14 <https://doi.org/10.1484/J.JUA.5.121525>.

——. 2020b. 'Urban Archaeology: A New Agenda – Editorial', *Journal of Urban Archaeology*, 1: 9–13 <https://doi.org/10.1484/J.JUA.5.120906>.

——. 2020c. 'Urban Networks and High-Definition Narratives: Rethinking the Archaeology of Urbanism', *Journal of Urban Archaeology*, 2: 173–86 <https://doi.org/10.1484/J.JUA.5.121535>.

Raja, R. and J. Steding (eds). 2021a. *Production Economy in Greater Roman Syria: Trade Networks and Production Processes*, Studies in Palmyrene Archaeology and History, 2 (Brepols: Turnhout).

——. 2021b. 'Production Economy in Roman Syria: New Views on Old Stones', in R. Raja and J. Steding (eds), *Production Economy in Greater Roman Syria: Trade Networks and Production Processes*, Studies in Palmyrene Archaeology and History, 2 (Brepols: Turnhout), pp. 1–8.

Rathbone, D. 2009. 'Earnings and Costs: Living Standards and the Roman Economy (First to Third Centuries AD)', in A. Bowman and A. I. Wilson (eds), *Quantifying the Roman Economy: Methods and Problems*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 299–326.

Redman, C. L. 2005. 'Resilience Theory in Archaeology', *American Anthropologist*, 107: 70–77 <https://doi.org/10.1525/aa.2005.107.1.070>.

——. 2019. 'The Impact of Food Production: Short-Term Strategies and Long-Term Consequences', in J. E. Jacobsen and J. Firor (eds), *Human Impact on the Environment: Ancient Roots, Current Challenges*, 1st edn (London: Routledge), pp. 35–49 <https://doi.org/10.4324/9780429037757-3>.

Redman, C. L. and A. P. Kinzig. 2003. 'Resilience of Past Landscapes: Resilience Theory, Society, and the *longue durée*', *Conservation Ecology*, 7.1 <https://www.jstor.org/stable/26271922> [accessed 3 February 2021].

Remesal Rodríguez, J. 2018. 'El Monte Testaccio (30 años de investigación)', *Tribuna d'arqueologia*, 2015–2016: 72–87.

Rice, C. 2016. 'Shipwreck Cargoes in the Western Mediterranean and the Organization of Roman Maritime Trade', *Journal of Roman Archaeology*, 29: 165–92.

Riede, F. 2009. 'Climate and Demography in Early Prehistory: Using Calibrated ^{14}C Dates as Population Proxies', *Human Biology*, 81: 309–37.

Rissman, P. 1988. 'Public Displays and Private Values: A Guide to Buried Wealth in Harappan Archaeology', *World Archaeology*, 20: 209–28.

Romanowska, I., O. Bobou, and R. Raja. 2021. 'Reconstructing the Social, Economic and Demographic Trends of Palmyra's Elite from Funerary Data', *Journal of Archaeological Science*, 133: 105432 <https://doi.org/10.1016/j.jas.2021.105432>.

Romanowska, I., A. Lichtenberger, and R. Raja. 2021. 'Trends in Ceramic Assemblages from the Northwest Quarter of Gerasa/Jerash, Jordan', *Journal of Archaeological Science: Reports*, 36: 102778 <https://doi.org/10.1016/j.jasrep.2020.102778>.

Romanowska, I., C. Wren, and S. Crabtree. 2021. *Agent-Based Modeling for Archaeology: Simulating the Complexity of Societies* (Santa Fe: Santa Fe Institute Press).

Römer-Strehl, C. 2013. 'Keramik', in A. Schmidt-Colinet and K. al-As'ad (eds), *Palmyras Reichtum durch weltweiten Handel: Archäologische Untersuchungen im Bereich der hellenistischen Stadt*, II: *Kleinfunde* (Vienna: Holzhausen), pp. 7–80.

Rösch, M. 2000. 'Long-Term Human Impact as Registered in an Upland Pollen Profile from the Southern Black Forest, South-Western Germany', *Vegetation History and Archaeobotany*, 9: 205–18 <https://doi.org/10.1007/BF01294635>.

Rosen, S. A. 2003. 'The Decline of Desert Agriculture: A View from the Classical Period Negev', in G. Barker and D. Gilbertson (eds), *The Archaeology of Drylands* (London: Routledge), pp. 44–62.

Rosenberg, N. 1963. 'Capital Goods, Technology, and Economic Growth', *Oxford Economic Papers*, 15: 217–27.

Rouhani, A. and R. Shahivand. 2020. 'Potential Ecological Risk Assessment of Heavy Metals in Archaeology on an Example of the Tappe Rivi (Iran)', *SN Applied Sciences*, 2: 1277 <https://doi.org/10.1007/s42452-020-3085-5>.

Rowan, E. 2017a. 'Bioarchaeological Preservation and Non-Elite Diet in the Bay of Naples: An Analysis of the Food Remains from the Cardo V Sewer at the Roman Site of Herculaneum', *Environmental Archaeology*, 22: 318–36.

——. 2017b. 'Sewers, Archaeobotany, and Diet at Pompeii and Herculaneum', in A. I. Wilson and M. Flohr (eds), *The Economy of Pompeii*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 111–34.

Ruddiman, W. F. 2007. 'The Early Anthropogenic Hypothesis: Challenges and Responses', *Reviews of Geophysics*, 45.4 <https://doi.org/10.1029/2006RG000207>.

Rue, D. J. 1987. 'Early Agriculture and Early Postclassic Maya Occupation in Western Honduras', *Nature*, 326.6110: 285–86 <https://doi.org/10.1038/326285a0>.

Ruffing, K. 2016. 'Driving Forces for Specialization: Market, Location Factors, Productivity Improvements', in A. I. Wilson and M. Flohr (eds), *Urban Craftsmen and Traders in the Roman World*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 115–31.

Russell, B. 2013. *The Economics of the Roman Stone Trade* (Oxford: Oxford University Press).

Saito, K. 'Palmyrene Burial Practices from Funerary Goods', in E. Cussini (ed.), *A Journey to Palmyra: Collected Essays to Remember Delbert R. Hillers* (Leiden: Brill), pp. 150–65.

Sallares, R. 2007. 'Ecology', in W. Scheidel, I. Morris, and R. P. Saller (eds), *The Cambridge Economic History of the Greco-Roman World*, 1st edn (Cambridge: Cambridge University Press), pp. 13–37 <https://doi.org/10.1017/CHOL9780521780537.003>.

Saller, R. 2005. 'Framing the Debate over Growth in the Ancient Economy', in J. G. Manning and I. Morris (eds), *The Ancient Economy: Evidence and Models* (Stanford: Stanford University Press), pp. 223–38.

Sartre, M. 2005. *The Middle East under Rome*, trans. by C. Porter and E. Rawlings (Cambridge, MA: Belknap).

Sartre-Fauriat, A. 2019. 'The Discovery and Reception of Palmyra', in A.-M. Nielsen and R. Raja (eds), *The Road to Palmyra* (Copenhagen: Ny Carlsberg Glyptotek), pp. 65–77.

Sartre-Fauriat, A. and M. Sartre. 2016. *Palmyre: vérités et légendes* (Paris: Perrin).

Savino, E. 1999. *Città di frontiera nell'Impero romano: forme della romanizzazione da Augusto ai Severi*, Pragmateiai, 1 (Bari: Edipuglia).

Scheidel, W. 2009. 'In Search of Roman Economic Growth', *Journal of Roman Archaeology*, 22: 46–70.

——. 2016. 'Empires of Inequality: Ancient China and Rome', *Princeton/Stanford Working Papers in Classics* <http://dx.doi.org/10.2139/ssrn.2817173>.

——. 2020. 'Roman Wealth and Wealth Inequality in Comparative Perspective', *Journal of Roman Archaeology*, 33: 341–53.

Scheidel, W. and S. J. Friesen. 2009. 'The Size of the Economy and the Distribution of Income in the Roman Empire', *Journal of Roman Studies*, 99: 61–91.

Schlumberger, D. 1951. *La Palmyrène du Nord-Ouest: villages et lieux de culte de l'époque impériale; recherches archéologiques sur la mise en valeur d'une région du désert par les Palmyréniens*, Bibliothèque archéologique et historique, 49 (Paris: Geuthner).

Schmidt-Colinet, A. 1990. 'Considérations sur les carrières de Palmyre', in M. Waelkens (ed.), *Pierre éternelle du Nil au Rhin: carrières et préfabrication* (Brussels: Crédit communal), pp. 88–92.
——. 1995. 'The Quarries of Palmyra', *ARAM Periodical*, 7: 53–58.
Schmidt-Colinet, A. and K. al-As'ad (eds). 2013. *Palmyras Reichtum durch weltweiten Handel: Archäologische Untersuchungen im Bereich der hellenistischen Stadt*, 2 vols (Vienna: Holzhausen).
Schmidt-Colinet, A., A. Stauffer, and K. al-As'ad. 2000. *Die Textilien aus Palmyra: Neue und alte Funde*, Damaszener Forschungen, 8 (Mainz: Von Zabern).
Seland, E. H. 2016. *Ships of the Desert and Ships of the Sea: Palmyra in the World Trade of the First Three Centuries CE*, Philippika, 101 (Wiesbaden: Harrassowitz).
——. 2018. 'Nomads and Caravan Trade in the Syrian Desert', in M. D. Frachetti and N. Boivin (eds), *Globalization in Prehistory: Contact, Exchange, and the 'People without History'* (Cambridge: Cambridge University Press), pp. 184–204 <https://doi.org/10.1017/9781108573276.009>.
Shifman, I. S. 2014. *The Palmyrene Tax Tariff*, trans. by S. Khobnya and ed. by J. F. Healey, Journal of Semitic Studies Supplement, 33 (Oxford: Oxford University Press).
Sidebotham, S. E., M. Hense, and H. M. Nouwens. 2008. *The Red Land: The Illustrated Archaeology of Egypt's Eastern Desert* (Cairo: American University in Cairo Press).
Sinner, A. G. and C. Carreras. 2019. 'Methods of Palaeodemography: The Case of the Iberian Oppida and Roman Cities in North-East Spain', *Oxford Journal of Archaeology*, 38: 302–24.
Slane, K. W. 2003. 'Corinth's Roman Pottery: Quantification and Meaning', *Corinth: Results of Excavations Conducted by the American School of Classical Studies at Athens*, 20: 321–35.
Smith II, A. M. 2013. *Roman Palmyra: Identity, Community, and State Formation* (Oxford: Oxford University Press).
Smith, M. E. 1987. 'Household Possessions and Wealth in Agrarian States: Implications for Archaeology', *Journal of Anthropological Archaeology*, 6: 297–335.
Sommer, M. 2018. *Palmyra: A History*, Cities of the Ancient World (New York: Routledge).
Stark, B. L. and C. P. Garraty. 2010. 'Detecting Marketplace Exchange in Archaeology: A Methodological Review', in B. L. Stark and C. P. Garraty (eds), *Archaeological Approaches to Market Exchange in Ancient Societies* (Boulder: University Press of Colorado), pp. 33–58.
Stern, D. I. 2004. 'The Rise and Fall of the Environmental Kuznets Curve', *World Development*, 32: 1419–39 <https://doi.org/10.1016/j.worlddev.2004.03.004>.
Stigler, G. J. 1951. 'The Division of Labor Is Limited by the Extent of the Market', *Journal of Political Economy*, 59: 185–93.
Temin, P. 2006. 'Estimating GDP in the Early Roman Empire', in E. Lo Cascio (ed.), *Innovazione tecnica e progresso economico nel mondo romano: atti degli incontri Capresi di storia dell'economia Antica (Capri 13–16 Aprile 2003)* (Bari: Edipuglia), pp. 31–54.
——. 2013. *The Roman Market Economy* (Princeton: Princeton University Press).
Terrenato, N. 2012. 'The Enigma of "Catonian" Villas: The *De agri cultura* in the Context of Second-Century BC Italian Architecture', in J. A. Becker and N. Terrenato (eds), *Roman Republican Villas: Architecture, Context, and Ideology*, Papers and Monographs of the American Academy in Rome, 23 (Ann Arbor: University of Michigan Press), pp. 69–93.
Torras, M. and J. K. Boyce. 1998. 'Income, Inequality, and Pollution: A Reassessment of the Environmental Kuznets Curve', *Ecological Economics*, 25: 147–60 <https://doi.org/10.1016/S0921-8009(97)00177-8>.
Tsiantikoudis, S., E. Zafeiriou, G. Kyriakopoulos, and G. Arabatzis. 2019. 'Revising the Environmental Kuznets Curve for Deforestation: An Empirical Study for Bulgaria', *Sustainability*, 11: 4364 <https://doi.org/10.3390/su11164364>.
Turchin, P. and W. Scheidel. 2009. 'Coin Hoards Speak of Population Declines in Ancient Rome', *Proceedings of the National Academy of Sciences of the United States of America*, 106: 17276–79 <https://doi.org/10.1073/pnas.0904576106>.
Verboven, K. S. 2007. 'Good for Business: The Roman Army and the Emergence of a "Business Class" in the Northwestern Provinces of the Roman Empire (1st Century BCE – 3rd Century CE)', in L. De Blois and E. Lo Cascio (eds), *The Impact of the Roman Army (200 BC – AD 476): Economic, Social, Political, Religious and Cultural Aspects*, Impact of Empire, 6 (Leiden: Brill), pp. 295–313.
——. 2018. 'Ancient Cliometrics and Archaeological Proxy-Data: Between the Devil and the Deep Blue Sea', in J. Remesal Rodríguez, V. R. Calvo, and J. M. Bermúdez Lorenzo (eds), *Cuantificar las economías antiguas: problemas y métodos*, Col·lecció instrumenta, 60 (Barcelona: Publicacions i edicions de la Universitat de Barcelona), pp. 345–71.
Walsh, K., P. Attema, and T. de Haas. 2014. 'The Pontine Marshes (Central Italy): A Case Study in Wetland Historical Ecology', *Babesch*, 89: 27–46.
Waltzing, J. P. 1895. *Etude historique sur les corporations professionnelles chez les romains depuis les origines jusqu'a la chute de l'empire d'Occident*, I (Leuven: Peeters).
Ward-Perkins, J. B. 1948. 'Severan Art and Architecture at Lepcis Magna', *Journal of Roman Studies*, 38: 59–80.

Wendrich, W. Z. and S. E Sidebotham. 2007. *Berenike 1999/2000: Report on the Excavations at Berenike, including Excavations in Wadi Kalalat and Siket, and the Survey of the Mons Smaragdus Region* (Los Angeles: Cotsen Institute of Archaeology).

White, A. J. 2017. 'Fecal Stanols as Indicators of Ancient Population Change' (unpublished master's thesis, California State University, Long Beach).

White, A. J., L. R. Stevens, V. Lorenzi, S. E. Munoz, C. P. Lipo, and S. Schroeder. 2018. 'An Evaluation of Fecal Stanols as Indicators of Population Change at Cahokia, Illinois', *Journal of Archaeological Science*, 93: 129–34.

Wilson, A. I. 2007. 'Urban Development in the Severan Empire', in S. Swain, S. Harrison, and J. Elsner (eds), *Severan Culture* (Cambridge: Cambridge University Press), pp. 290–326.

——. 2008. 'Machines in Greek and Roman Technology', in J. P. Oleson (ed.), *The Oxford Handbook of Engineering and Technology in the Classical World* (Oxford: Oxford University Press), pp. 337–66.

——. 2009. 'Indicators for Roman Economic Growth: A Response to Walter Scheidel', *Journal of Roman Archaeology*, 22: 71–82.

——. 2011a. 'City Sizes and Urbanization in the Roman Empire', in A. Bowman and A. I. Wilson (eds), *Settlement, Urbanization, and Population*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 161–95.

——. 2011b. 'Developments in Mediterranean Shipping and Maritime Trade from the Hellenistic Period to AD 1000', in D. Robinson and A. I. Wilson (eds), *Maritime Archaeology and Ancient Trade in the Mediterranean* (Oxford: Oxford Centre for Maritime Archaeology), pp. 33–59.

——. 2012. 'Water, Power and Culture in the Roman and Byzantine Worlds: An Introduction', *Water History*, 4: 1–9 <https://doi.org/10.1007/s12685-012-0050-2>.

——. 2014. 'Quantifying Roman Economic Performance by Means of Proxies: Pitfalls and Potential', in F. Callataÿ (ed.), *Quantifying the Greco-Roman Economy and Beyond* (Bari: Edipuglia), pp. 147–68.

——. 2020. 'Roman Water-Power', in P. Erdkamp, K. Verboven, and A. Zuiderhoek (eds), *Capital, Investment, and Innovation in the Roman World*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 147–94.

Wilson, A. I. and A. Bowman. 2017. 'Introduction', in A. I. Wilson and A. Bowman (eds), *Trade, Commerce, and the State in the Roman World*, Oxford Studies on the Roman Economy (Oxford: Oxford University Press), pp. 1–24.

Wilson, D. C. 1994. 'Identification and Assessment of Secondary Refuse Aggregates', *Journal of Archaeological Method and Theory*, 1: 41–68.

Wiseman, J. 2007. 'Environmental Deterioration and Human Agency in Ancient Macedonia: A Case Study', *Geoarchaeology*, 22: 85–110 <https://doi.org/10.1002/gea.20148>.

Witcher, R. E. 2005. 'The Extended Metropolis: *Urbs*, *suburbium* and Population', *Journal of Roman Archaeology*, 18: 120–38.

Wörrle, M. 1989. *Stadt und Fest im kaiserzeitlichen Kleinasien: Studien zu einer agonistischen Stiftung aus Oenoanda* (Munich: Vestiga).

Yamamura, K. and W. J. Duffy. 1971. 'Monetization and Integration of Markets in Tokugawa Japan: A Spectral Analysis', *Explorations in Economic History*, 8: 395–423.

Yon, J.-B. 2002. *Les Notables de Palmyre*, Bibliothèque archéologique et historique, 163 (Beirut: Presses de l'Ifpo).

——. 2012. *Inscriptions grecques et latines de la Syrie*, XVII.1: *Palmyre* (Beirut: Institut français du Proche Orient).

——. 2019. 'Palmyra and its Elites', in A.-M. Nielsen and R. Raja (eds), *The Road to Palmyra* (Copenhagen: Ny Carlberg Glyptotek), pp. 91–108.

Yu Qiao. 1998. 'Capital Investment, International Trade and Economic Growth in China: Evidence in the 1980–1990s', *China Economic Review*, 9: 73–84.