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Mediterranean land use systems from prehistory to antiquity: a case study from Peloponnese (Greece)

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ABSTRACT

Understanding the sustainability of land use systems over time requires an accounting of the diversity of land uses and their varying influences on the environment. Here we present a standardized review of land use systems in the Peloponnese, Greece, from the Neolithic to the Roman period (~6500 BC–AD 300). Using a combination of sources, we synthesize the fundamental information required to characterize and quantify the spatial requirements of land use. We contextualize our results in a discussion of temporal trends, the probable drivers of change, and how these changes can be integrated with the general knowledge of these societies and the overall effect of land use across time. While our review concentrates on the Peloponnese, our methodology is widely applicable where suitable archaeological and historical records are available, and is broadly representative of the prehistoric and early historical evolution of agricultural land use systems in the eastern Mediterranean.

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Sustainable land use; land use modelling; human–environment interactions; Aegean prehistory; classical antiquity; Greece


1. Introduction

Land use is the fundamental basis of most human societies. Humans have exploited landscapes for foraging and hunting throughout their history, and with growing extent and intensity over the last ca. 12,000 years, for agriculture and animal production. Because of its long history and pervasive spatial extent, land use represents the first major influence that humans had on the earth system. Starting in prehistory, land use led to changes in regional and global climate, biogeochemical cycles, biodiversity, and the global distribution of plants and animals (e.g. Boivin et al., 2016). Land use further defines one of the primary ways humans interact with their environment. Factors that perturb land use, such as climate variability or overexploitation of natural resources, may lead to situations where populations become vulnerable to demographic swings, migration, or conflict (e.g. Turchin, Currie, Turner, & Gavrillets, 2013). Understanding how, when, and where land use developed and evolved over time is therefore valuable both for evaluating the present and future state of the earth system, and for identifying the causes of social instability during periods of environmental change.

At any given time, the properties of the physical environment provide absolute constraints on the types of land use that are possible. For example, most cereal crops require neither too much nor too little rainfall to produce a harvest (e.g. Fischer, Van Velthuizen, Shah, & Nachtergaele, 2002).

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Some domesticated animals tolerate heat and high temperatures while others are better adapted to colder climates (Hoffmann, 2010; Nardone, Ronchi, Lacetera, & Bernabucci, 2006). Specific land uses are thus typically associated with certain environmental conditions (e.g. Iizumi & Ramankutty, 2015). However, the physical environment alone does not determine land use. The land use that occurs in any given place and time is a function of the socio-cultural characteristics of the people who live there (Grigg, 1974). Their diet, technology, land management practices, social organization, and trade networks all influence the expression of land use on the landscape, population density, and the relative impact that any given land use has on the environment.

For the present-day, it is possible to map the large-scale patterns of land use through a combination of observations and some form of census techniques that allow characterization of socio-cultural attributes. Satellite remote sensing, for example, provides a view of land cover, which frequently can be associated to various forms of contemporary land use (e.g. Ellis & Ramankutty, 2008). When combined with global and regional statistics on, e.g., crop production, it has become possible to estimate the spatial extent of a number of agricultural cropping systems (e.g. Monfreda, Ramankutty, & Foley, 2008). Other forms of land use, such as pastures and rangelands dedicated to animal production, are harder to detect and differentiate but new techniques are being developed (e.g. Phelps & Kaplan, 2017). For periods predating the advent of large-scale mapping and collection of economic and agricultural statistics, however, generating a synthetic picture of land use and understanding its relevance for anthropogenic land cover change is much more difficult. In the present paper, we provide the results of a study designed to contribute to both these issues.

1.1 Scenarios of past land use change

Current scenarios of anthropogenic land cover change over the pre-satellite era – these typically cover the most recent few centuries (Klein Goldewijk, 2001; Ramankutty & Foley, 1999), the last millennium (Pongratz, Reick, Raddatz, & Claussen, 2008), or the mid- to late-Holocene (Kaplan et al., 2011; Klein Goldewijk, Beusen, Doelman, & Stehfest, 2017; Klein Goldewijk, Beusen, van Drecht, & de Vos, 2011) – principally rely on a relationship between human population and land demand, i.e. per capita land use. Driven by a spatially explicit time series of population, total land use is calculated on the basis of per capita demand, and distributed as a function of properties of the physical environment, e.g., temperature and soil quality (e.g. Kaplan, Krumhardt, & Zimmermann, 2009; Ramankutty, Foley, Norman, & McSweeney, 2002). While these scenarios are widely applied, e.g., as a boundary condition for climate modeling (Schmidt et al., 2012) or for understanding changes in terrestrial carbon storage over time (e.g. Kaplan, Krumhardt, & Zimmermann, 2012; Kuemmerle et al., 2015; Pongratz, Reick, Raddatz, & Claussen, 2009), they vary wildly in their representation of both the temporal evolution and spatial distribution of land use over time (e.g. Ellis et al., 2013; Gaillard et al., 2010; Harrison, Stocker, Klein Goldewijk, Kaplan, & Braconnot, 2018). Given these large uncertainties, and the importance of land use for many aspects of earth system science, improving scenarios of prehistoric and preindustrial anthropogenic land cover change has been identified as a priority for the community (Harrison et al., unpublished).

Such scenarios would need to entail reconstructions of both the physical environment, e.g., climate and land cover, and ancient utilization of it, i.e. land use. On Holocene and more recent timescales, the properties of the physical environment are reasonably well constrained by paleoclimate and paleoecological reconstructions, and many records have been synthesized at continental to global scales (e.g. Wanner et al., 2008), which should make the use of this information relatively straightforward in the development of future scenarios. But while changes in the properties of the physical environment may have played an important role in influencing some aspects of past land use, particularly in environments that were marginal for agriculture and animal production, the largest source of uncertainty in these scenarios comes from the per capita land use relationship used as the fundamental translation of an estimate of

human population to land demand. Under uniform environmental conditions, per capita land use is governed by socio-cultural attributes including diet, technology, management practices, social organization, and tribute and trade. In contrast to paleoenvironmental studies, socio-cultural attributes governing past land use have only recently been elucidated in a common framework (Morrison et al., 2018), and are not yet widely available for most regions and periods in the past.

One way to approach understanding the role of socio-cultural attributes in influencing land use change is to adopt one or more middle-range theories on the drivers of land use (e.g. Boserup, 1965; Geertz, 1963; Grigg, 1974; Malthus, 1798; Ruthenberg, 1971). These theories provide a framework to predict human responses to changing demographic, technological, environmental, and political conditions, and indeed, the application of such theories is essential in attempting to predict future land use and anthropogenic land cover change (Meyfroidt et al., 2018). When considering the past, we may, by contrast, adopt a data-driven approach, in which we attempt to extract the socio-cultural attributes influencing land use from the archaeological and historical record. One advantage of such an approach is that it may allow us to reconstruct past land use patterns in a way that is agnostic of any particular theory, and therefore to evaluate different theories *a posteriori* in light of the evidence.

1.2 Ancient land use in the Peloponnese

In many parts of the world, the archaeological and historical record is sufficient to produce a general picture of land use over time. In this study, we consider a sub-region of the eastern Mediterranean, the Peloponnese peninsula of southern Greece. The Peloponnese has been continuously occupied by agricultural societies since ~6500 BC, it has a history of gradual and rapid changes in material culture, apparent demographic dynamics, and the early appearance of complex societies including extensive trade networks and early writing systems (Weiberg et al., 2016). The peninsula is thus particularly interesting for evaluating middle-range theories of land use change, and how land use affected, and were in turn affected by, changes in the physical environment.

In the present study, we exploit the information provided in archaeological and historical records in order to estimate cultural and technological change in the Peloponnese (Hughes, Weiberg, Bonnier, Finné, & Kaplan, 2018; Kay & Kaplan, 2015). Rather than attempting a comprehensive reconstruction of all details of human land use and their variability over time, we concentrate on defining the parameters and variables governing land use that are common across periods. We synthesize the socio-cultural attributes required to characterize and quantify land use, including diet, animal species exploited, technology and material culture, and social organization. We describe the scale of human presence on the landscape in terms of typical per capita land requirements. We show how this 'land footprint' (Steen-Olsen, Weinzettel, Cranston, Ercin, & Hertwich, 2012) changed with time, to highlight how per capita land use evolved under changing sociocultural conditions. Our results form a basis not only for our long-term research aim of understanding societal vulnerability and resilience in the face of climate and other environmental change, but may also be used to evaluate middle-range theories of land use change (Meyfroidt et al., 2018), and ultimately improve our confidence in models and scenarios of past and future anthropogenic land cover change.

In the following sections, we briefly present our method and primary sources of data followed by a synthesis of the results. We contextualize our results in a discussion of the temporal trends in land use that emerged in the Peloponnese, the probable drivers of that change, and how these changes can be integrated with the general knowledge of these societies and the overall effect of land use across time. With the overall objective of understanding per capita land use in the past, we use archaeological and historical data to address the question: what was per capita land use in the ancient Peloponnese, and how did it change over time?

2. Study area and period

The Peloponnese peninsula has an area of approximately 21,550 km², more than 50% of which is comprised of steep mountains, interspersed with interior valleys and plains in the interior and along the coast (Figure 1). Our study covers the roughly 7000-year-long period from the Early Neolithic (~6500 BC) to the end of the Middle Roman period (AD 300). We divided this period into twelve chronological intervals based on the principle phases recognized by archaeologists and historians, with some deviations to more clearly distinguish the important temporal boundaries marking changes in land use systems (Figure 2).

Social structures during our 7000-year period of study were highly dynamic and are characterized by major, nonlinear cultural and socio-political transformations, including periods of nucleation and dispersal, and changing connectivity patterns, technologies, trade, and political control (Weiberg et al., 2016). The variations have implications for the overall picture of land use in different periods and are partly imprinted on the land cover change records of the region. A recent synthesis of palynological data from southern Greece (Weiberg et al., 2019), shows constant fluctuations of anthropogenic indicators, indicative of a continuously changing landscape over the relative short-term. This is also attested by fluctuations in the arboreal sum (a proxy for tree cover) indicating alternating periods of opening of the landscape, followed by regenerations of forests. Long-term trends can be seen for deciduous oak woods, which show high levels in the Neolithic but decrease gradually over the subsequent millennia to stabilize at a new, lower level from the Late Bronze Age. During this process, the deciduous oak woods are partly replaced by pines and other tree taxa. This change was likely driven by a combination of anthropogenic and climatological factors (Weiberg et al., 2019). Overall, the period from the Late Bronze Age to the early Roman times (~1500 BC–AD 100) is marked by strong human impact on the landscapes of southern Greece.

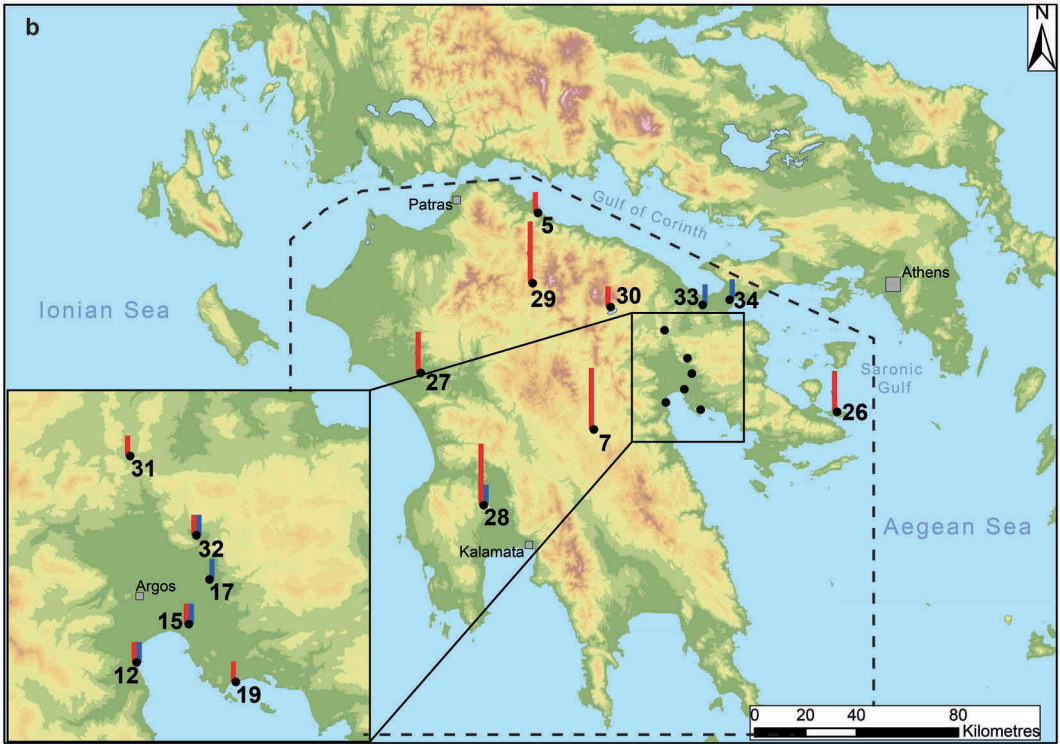
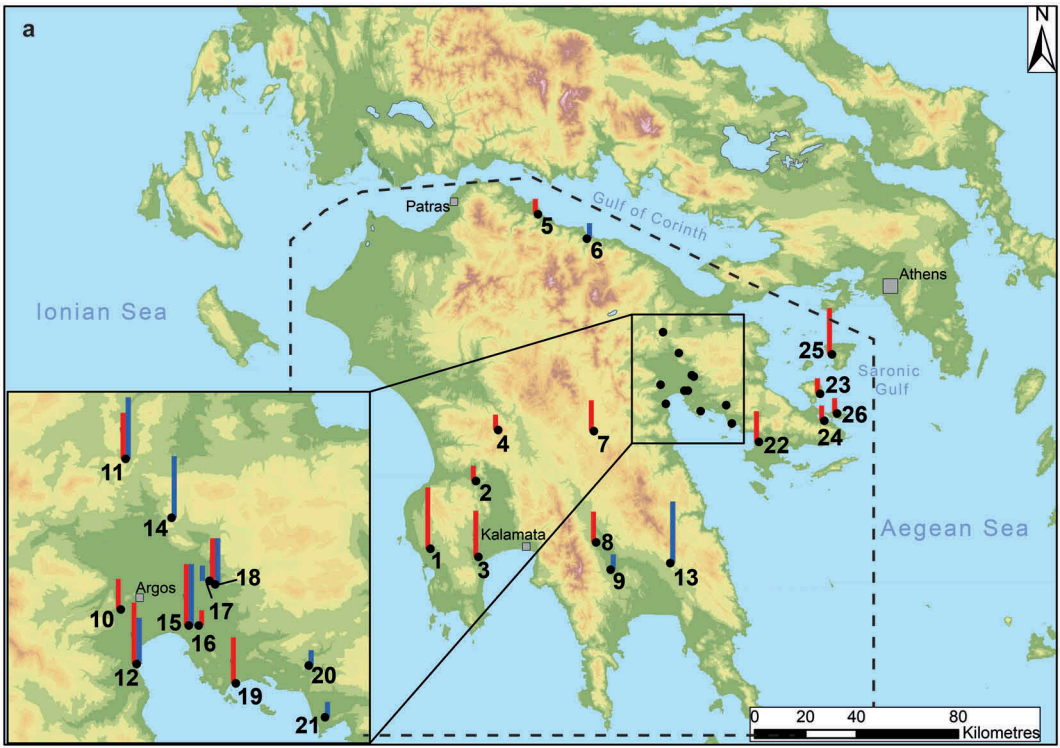
3. Methods

3.1. Quantifying per capita land use

The concept of quantifying the environmental footprint of a land use system using archaeological data was developed for sub-Saharan Africa (Kay & Kaplan, 2015), building on schematic reconstructions of land use in Neolithic Europe (Gregg, 1988). Here we employ a more advanced version of this methodology in terms of representativeness and complexity (Hughes et al., 2018), which forms the basis of a new, flexible land use model. Following Kay and Kaplan (2015), the model defines a hierarchy of land uses based on the relative influence an activity has on the local environment. For the Peloponnese, we define the following primary land use types in descending order of human energy inputs: 1) field crop cultivation, 2) tree crops and woodlot, and 3) livestock pasturage. Within each of these top-level categories, a range of more specific land use types may be defined that further influence the particular expression of land use on the landscape, e.g. bread wheat vs. barley cultivation among the field crops, or land dedicated to cows vs. goats in the pasturage category. The input to the land use model is a suite of parameters that define diet, agricultural practices, livestock species, and industrial activities such as metallurgy. For the Peloponnese, we defined these parameters on the basis of a broad synthesis of archaeological data and historical records, supplemented by contemporary measurements when no ancient data was available, e.g. on the caloric content of various crops. The evidence and assumptions behind the parameters are detailed in the Supplemental Appendix. The methodology and calculations are detailed by Hughes and colleagues (2018), including a flow chart overview of the interconnections between the different land use parameters.

3.2. Peloponnesian parameters

The parameters of ancient land use included in the calculations are outlined in Table 1, in which aspects of cultivation strategies relevant for more than one land use type are listed separately. The



timing of the introduction of specific livestock and crop species, as well as the relative proportions of these animals and crops was estimated from published analyses of seeds and animal bones from excavated settlements throughout the Peloponnese (and the nearby islands of Poros and Aegina) (Figure 1). The archaeological record also provides detail on societal structure and other aspects relevant for ancient land use (for example technological innovations such as the introduction of the plough or the development of metal use). Historical sources allow further insights into ancient views on land use, animal husbandry, and agricultural production (such as information on pasture rights provided by specific cities and the content of pastoral production in specific regions, see Whittaker, 1988). Finally, available literature on ancient land use pertaining to other parts of the ancient Mediterranean, as well as ethnographic work on premodern (pre-industrial) land use provide valuable complementary information (e.g. Forbes, 2012b; Halstead, 2014). In many cases, the sources are combined to give a fuller picture and our reconstructions of diet are, for example, based on a combination of historical sources and recent paleodietary reconstructions (Nitsch et al., 2017; Papathanasiou, Richards, & Fox, 2015).

In addition, to the dietary and basic energy consumption requirements that controlled land use, the organization of societies (writ large) placed an important top-down control on human influence on Peloponnesian landscapes over the Holocene. Variations in this organization can be observed archaeologically through the scale of human activities and inferred societal structures, and through the range and complexity of observed and recorded material culture. On a general level, ancient societies became over time, increasingly more complex, i.e. 'comprised of more parts, more kinds of parts, and greater integration of parts' (Tainter, 2000, p. 6). This development, however, was not linear.

To incorporate something of this variability into our land use assessments, we developed a generalized societal complexity index (SCI) as an input to our model. The SCI ranges from 1 (low) to 5 (very high) (Figure 2) and is a qualitative assessment of the scale of human activities as reflected by the number, distribution and/or size of recognized archaeological sites/settlements, and inferred from socio-economic and hierarchical structures, contact networks as well as the range and diversity of material culture. As an example, a society classified as SCI 1 is a mostly egalitarian, household structured society with few external contacts, a limited material culture repertoire and little craft specialization. A society classified as SCI 5, on the other hand, is one with comprehensive and formalized socio-political hierarchical structures with many specialized roles, including craft production and other economic activities, within complex regional and supra-regional contact networks. SCI 2–4 reflect a qualitative assessment in relation to these two extremes.

Changes in the scale of human activity – as marked out by our prescribed changes in the SCI – are inscribed on the landscape and represent changes in the both the extent and intensity of land use, and are often assumed to reflect changes in the population level. Although the causal relationship between population size and measures of intensification remains unclear, a link between growing demand and measures to increase productivity may be assumed (Ellis et al., 2013; Meyfroidt et al., 2018). We generally assume that with increased societal complexity comes greater ability to harness resources for the upkeep of resource demanding auxiliary animals, as well as to organize the human labor needed for an increased production and cultivation (in terms of input and/or scale).

Figure 1. Map of the Peloponnese indicating the availability of archaeobotanical (blue bars) and zooarchaeological records (red bars) during (A) prehistory (Phases 1–8) and during (B) historical periods (Phases 9–12). Height of the bars indicates the size of each assemblage. For further details, see Supplemental Appendix: Tables A4 and A5. 1: Pylos; 2: Malthi; 3: Nichoria; 4: Lykaion; 5: Helike; 6: Kassaneva; 7: Tegea; 8: Kouphovouno; 9: Agios Vasileios; 10: Argos; 11: Tsoungiza; 12: Lerna; 13: Geraki; 14: Mycenae; 15: Tiryns; 16: Profitis Elias; 17: Dendra; 18: Midea; 19: Asine; 20: Synoro; 21: Iria; 22: Franchthi; 23: Agios Konstantinos; 24: Galatas; 25: Kolonna; 26: Kalaureia; 27: Olympia; 28: Messene; 29: Lousoi; 30: Stymphalos; 31: Nemea; 32: Pyrgouthi; 33: Corinth; 34: Isthmia. The modern cities Patras, Argos and Kalamata are marked out and the box represents the dense distribution of archaeological sites on the Argive Plain. The full extent of the studied region is outlined by a dashed line.

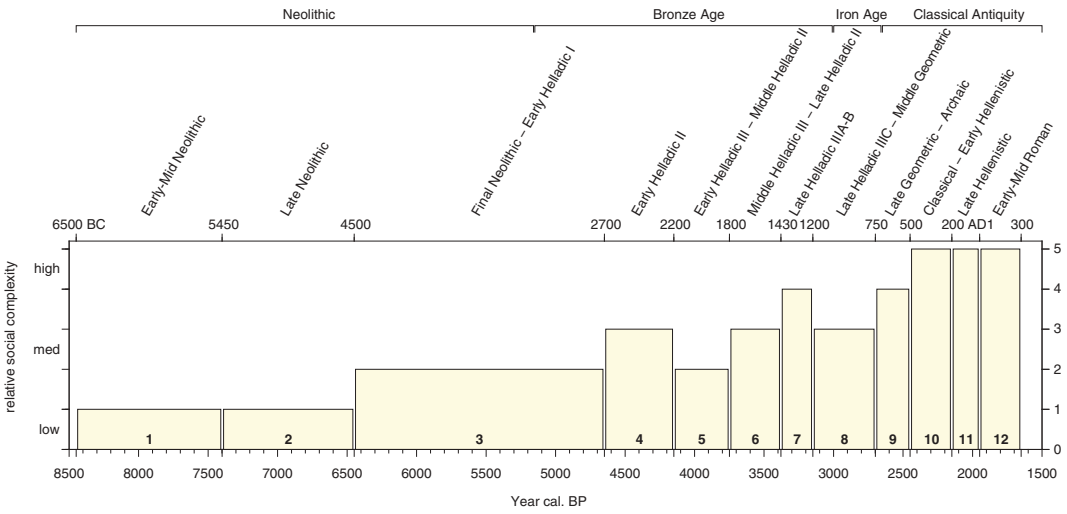


Figure 2. Timeline for the case study, including the twelve phases used and the associated relative chronological terminology. Each chronological phase is represented by a bar and the height of the bar indicate the prescribed societal complexity for that phase. The phases are numbered (bold digits) and these numbers are used throughout the paper and the Supplemental Appendix. The absolute chronology is presented as both dates before present (BP, where present is defined to AD 1950) and BC/AD dates (transition dates between phases only). Note that the length of the phases vary considerably (a result of the varying chronological resolution of the archaeological and historical record).

Table 1. Parameters considered for the assessment of ancient land use in the Peloponnese across time (for further details see Supplement Appendix).

Main parameters	Parameter specification	Land use type
Cattle		Pasturage
Sheep/Goat		
Pig		
Other domestic animals	<i>Horse; donkey; mule; dog; chicken</i>	
Secondary products	<i>Milk; cheese; fleece; labour/transport</i>	
Barley		Field crops
Wheat	<i>Einkorn; emmer; bread wheat; spelt</i>	
Legumes	<i>Bitter vetch; lentil; pea; broad bean; grass pea; other</i>	
Flax		
Other cereals	<i>Millet; oat; rye</i>	
Olive cultivation	<i>Diet; bathing; lighting; firewood</i>	Tree crops and woodlot exploitation
Viticulture		
Other tree crops	<i>Almond; fig; pistachio; acorn; peach; apple; other</i>	
Firewood	<i>Cooking; heating</i>	
Ceramics production		Cultivation strategy
Metal working	<i>Bronze; iron</i>	
Charcoal production		
Settlement production		
Storage and loss	<i>Food storage; loss; reseeding</i>	
Productivity	<i>Yield; draft oxen</i>	

We used the SCI index as a relative measure of general societal complexity for each of the twelve chronological phases as a whole, to include aspects of land use that were present but which cannot be quantified given the current archaeological and historical records, for example, the numbers of mules, horses and oxen raised per capita, flax and pottery consumption and typical crop yields all depend on the SCI. In the assessments, it is assumed that work animals (representing increasing efficiency), flax and pottery consumption (reflecting increased demand met by increased production) were more prevalent in societies with high SCI than in those with a low SCI. On the

other hand, crop yields per unit area are prescribed to decline with increasing SCI, in recognition of the observations that urbanized societies in past Mediterranean and southwest Asian contexts tended to increase the spatial extent of cultivation, while simultaneously showing less evidence of manuring and weeding compared to smaller scale, intensive systems (Halstead, 2000; Styring et al., 2017). In this scenario, yields per unit area will decrease but the overall productivity still increases due to the larger extent of the cultivated areas, technological innovations and/or crop choices.

The SCI adds an additional layer of conjecture to the calculations based on available evidence that is not quantifiable. Through the incorporation of unquantifiable parameters in the SCI, however, important land use components are added and the non-linearity of changes over time throughout the 7000 years of the study period is emphasized. Overall, the SCI-driven increase in per capita spatial requirements accounts for a maximum of ~20% of the total increase indicating that other factors were more significant. The SCI-driven part of the spatial requirements increases from SCI 1–5 but does never account for more than 12% of the overall output.

3.3. Limitations and issues of generalization

This study presents a model that integrates many disparate sets of evidence and all available records have specific limitations that need to be addressed. These limitations pertain to input variables as well as output. Most importantly, our results will inevitably be colored by the availability of detailed and quantifiable data, which in turn are the sum of the very varied chronological, geographical and thematic emphases of previous research. There is, for instance, overall more zooarchaeological studies than there are archaeobotanical studies (Figure 1). There is also a relative lack of archaeobotanical and zooarchaeological data for the historical periods, for which information from available textual sources have been given priority. Unfortunately, these texts seldom relate to specific Peloponnesian contexts, which hampers our understanding of regionally specific characteristics. From a geographical perspective, there is a research emphasis on the northeast Peloponnese but the record even from this region is far from homogeneous. Differences between settlements are likely due to factors such as landscape position (e.g. coastal vs. upland, influencing for example diet through the availability of different food types) or function (e.g. domestic, funerary, or religious, influencing the relative frequencies of animals and crops recoverable in these settings as the main activities, e.g. daily food preparation or sacrifices, influence the choice of crop or animals).

The land use assessments presented here should be seen as a generalization of the *typical* or *average* land use for each of the twelve phases. In its present form, for example, the land use assessments do not resolve spatial variations in land use. In reality, as an extension of the variation noted even within the northeast Peloponnese, there would have been significant spatial variability in the patterns of land use within each phase, e.g. between a coastal town and a mountain settlement. It is therefore important that the potential effects of such variability are highlighted and included in any future spatial operationalization of the results. For the present purpose, however, our focus on quantifying the typical land use pattern in each phase provides an opportunity to reach beyond the local and to make our results relevant on a regional scale, and potentially beyond.

Archaeobotanical and zooarchaeological data synthesized for this study have their own method-specific limitations relating to, for example, sample size, method of collection, identification protocols and the impact of taphonomic processes (e.g. Lyman, 2008). Similar caution relates to the use of textual sources, which are always biased by the motivations of their authors. In addition, any modern reconstruction of the past will run the risk of not identifying important parameters for ancient land use, whether because of modern misconceptions or the fragmentary nature of ancient records. In synthesizing data with such a wide spectrum of limitations, the present work must be conducted with a level of generalization not often employed in archaeological research. All of the assumptions and numbers presented in this paper come with uncertainties and also mask a great deal of variability, and our quantifications should be revisited as new data are made available. In

terms of uncertainties of output, it should be emphasized that the current version of our land use assessment is only concerned with the spatial requirements for household subsistence needs. Production for export is not included, even though some degree of cash cropping has been assumed for at least periods 10, 11 and 12 (see for example Bresson, 2016, pp. 170–174; Papadopoulos & Morris, 2005; Rizakis, 2013) and large-scale production of ceramics for export is known to have occurred in phases 7, 9 and 10, sometimes connected to the export of wine, oils or other contents. Also excluded in our calculations are resource consumption for extraordinary activities, such as shipbuilding and monumental construction. All of these activities may have had a considerable effect on land use requirements at certain times and places. It should also be noted that our quantifications and hence the output is demand-based, i.e. we do not specify the actual location of the cultivated fields or pasturage. The stipulated needs could thus be fulfilled through the import of goods from areas beyond the local environment, a factor that was certainly locally important in the final phases of our study period.

Diet and yield both have a strong effect on the output of the model and are also exceedingly difficult to reconstruct for ancient times. In the present study, like all other input data, these parameters have been generalized. As highlighted by Hughes and colleagues (2018), however, the quantification method is designed to be flexible and changing the input data on yields and diets allows alternative scenarios to be tested. The input can thereby be revised for specific conditions, e.g. diet differentiated by social status or crop yield by certain soil capabilities.

4. Results

Using the synthesis of archaeological and historical data as input to our land use model, we calculated the typical spatial requirements for human subsistence in the Peloponnese over time. The model outputs are organized into the three primary land use types in Figure 3 and a detailed breakdown of all of the different land uses is presented in Figure 4. Throughout our period of study, the predominant forms of land use in the Peloponnese were pasturage and field crop cultivation, but these were complemented by tree crop and woodland exploitation, and to a much lesser degree, area dedicated to settlements. The results can be summarized in the following main points:

- Per capita land use increased by 60% from 2.0 ha in the Final Neolithic-Early Helladic I (Phase 3) to 3.2 ha in the Classical to Hellenistic periods (Phases 10–11).
- Per capita land use for pasturage almost double (1.1–1.9 ha) over this period and the field crop area expands progressively from 0.8 to 1.1 ha. Tree crops and woodland exploitation

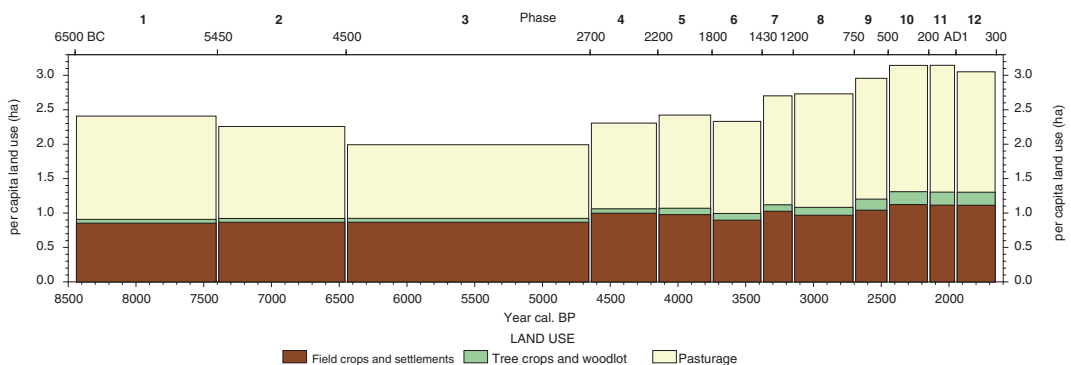


Figure 3. Per capita calculations of land use throughout the twelve phases displayed in hectare values. Land use is categorized by the three primary land use types: field crops, tree crops and woodlot, and pasturage.

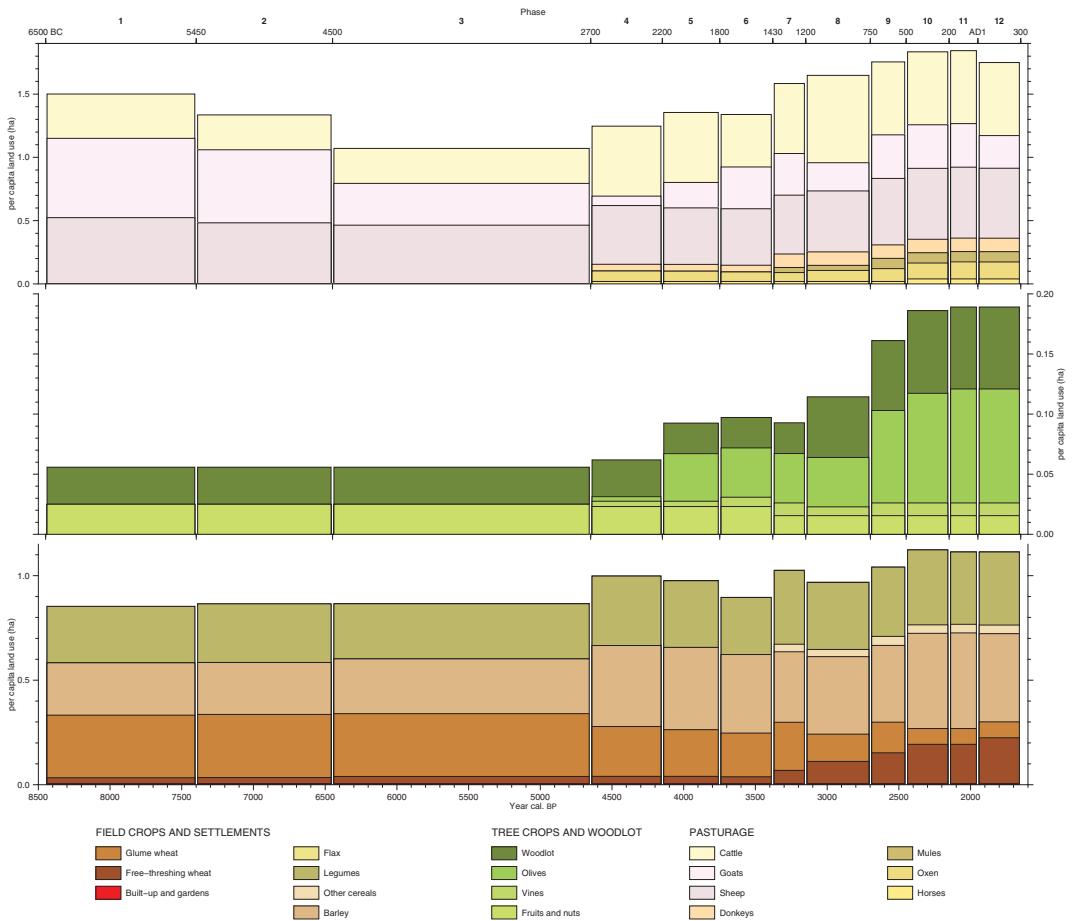


Figure 4. The full variety of land use parameters included in the per capita calculations of land use. The three panels show each one of the three primary land use types: field crops (bottom panel), tree crops and woodlot (middle panel) and pasturage (top panel), and their specific land use parameters. Note that the scale differs between the three panels, for comparison see [Figure 3](#). The order of the categories is the same in the legend as in the panels.

were marginal in comparison with field crops and pasturage but increase strongly from 0.06 to 0.19 ha (+217%).

- A continuous diversification is apparent, especially from the Late Helladic III period (Phase 7), with new animals and plants being introduced, adding to, as opposed to supplanting, existing ones. One notable exception is the slow displacement of glume wheats in favor of free-threshing varieties.

Although the greatest increase in spatial requirements over time is for tree crops and woodlot exploitation, this land use type never exceeded 6% (Phase 12) of the total land requirements. The most significant increase in demand for woodlot area can be connected to iron production and working in the historical period, but there is also a noticeable increase in olive and olive oil production in the same period. Field crop cultivation comprises ~38% of total land use, largely motivated by human and animal consumption needs, and the change over time is primarily driven by changes of the yield, defined by the SCI, as well as the need for fodder crops, primarily barley, to feed increasing numbers of oxen and other work animals. This change over time is partly negated by a decrease of cereal consumption as diets became more diversified over time (Supplemental Appendix: Table A1).

Pasturage, finally, makes up the largest category, responsible for ~58% of the total land requirement in each of the twelve phases. The almost doubling of the per capita values for pasturage over time, is primarily due to the introduction of traction animals, but also to an increased use of secondary products, which, considering the low meat and dairy consumption in these past societies (we prescribed little or no change over time: see Supplemental Appendix), indicates that change in this category is largely unrelated to diet.

Diet is nevertheless the main contributor to the baseline requirements of land in any one of the periods. Changes in the proportion of animals will thus have an effect, as highlighted by the reduction in per capita land use between Phases 1 and 3, due to the strong decrease of sheep/goat in favor of pigs apparent in archaeozoological assemblages. Currently, we do not consider a distinct land area for pig husbandry because it is unclear to what extent separate pastures were arranged for pigs (Frémondeau, De Cupere, Evin, & Van Neer, 2017; Halstead & Isaakidou, 2011; Price, Krigbaum, & Shelton, 2017). Changes in pig meat consumption have a secondary effect on land requirements, however, decreasing the effect of other meat sources, and, if pigs were to be included in the pasturage category along with cattle, sheep and goats, the land demand for pasturage would increase significantly. A case in point is the small reduction in land requirement during the Roman period (Phase 12), which is the effect of an often assumed increased consumption of pig meat relative to meat from cattle or sheep/goat (Figure 4; assumptions of the growing importance of pork consumption in the Roman period is based on archaeological data from other provinces of the empire though these should be regarded as tentative given the paucity of local evidence, see King, 1999; MacKinnon, 2004).

5. Discussion

As noted above, our calculations include a range of assumptions and uncertainties, not the least in reconstructing diets and typical yields (Hughes et al., 2018). Nevertheless, it is instructive to compare our estimates of per capita land use with those suggested by other studies. Estimates of per capita land use for ancient Peloponnesian societies are few but our results for field crop cultivation are in good accordance with independent estimates for the Early Helladic (equivalent to our Phase 4) settlement of Tsoungiza, in the northeast Peloponnese (Hansen & Allen, 2011). The authors estimate that a population of 200 inhabitants would require about 120 hectares worth of cereals, i.e. 0.6 ha per capita, which would largely be the equivalent of the arable land available in this small inland valley (Hansen & Allen, 2011, pp. 885–886). In contrast, Bintliff (1977, p. 697) suggests that a holding of 7 hectares arable land was required to support 5 people, i.e. 1.4 ha per capita. Our estimates of demand for cropland fall in between these estimates (1 ha per capita for Phase 4), and this estimate includes an annual loss of harvest, stores for reseeding as well as production for animal fodder (see Supplemental Appendix). Our study also assumes slightly higher yields than those estimated for the Tsoungiza scenario, which implies that, if anything, our calculations may underestimate overall land demand.

It is further valuable to place our results in the context of the per capita land use parameters used to drive global and regional scenarios of anthropogenic land cover change. The HYDE 3.2 scenario (Klein Goldewijk et al., 2017) provides gridded fields of both population and land use area, so per capita land use can be calculated. Summing cropland and grazing land area and dividing by population shows that mean per capita land use in the Peloponnese in HYDE 3.2 is nearly constant at about 0.03 ha per person ($1\sigma \pm 0.14$) across the entire period from 6000 BC to AD 200 – the global average value in HYDE 3.2 in the AD 0 map is 0.5 ha per person. The range of per capita land use in in HYDE 3.2 in the Peloponnese is thus 20–100 times smaller than our estimates and therefore inconsistent with our reconstructions in both its absolute magnitude and temporal evolution. On the other hand, the KK10 scenario shows values in the Peloponnese around 4 ha per person and an average for Western Europe ranging from 5.5–6.5 over our study period (see Figure 2 in Kaplan et al., 2011). Ruddiman and Ellis (2009) likewise estimate a range of 2–6 ha per capita for early agriculturalists. In providing a detailed, bottom-up, data driven estimate of per capita land use and its change over time, our results will invariably be useful for the development of improved scenarios of anthropogenic land cover change in the future.

5.1. Drivers of land use change

In our calculations, the principle contributors to changing per capita land use over time consist of new additions to the range of human activities, notably work animals (pasturage and fodder), the growing importance of olive cultivation (oil for multiple purposes), and metallurgy (Figure 5). The introduction of iron, for example, together with the initiation of orchard cultivation, are the two main drivers of the increased spatial requirements for tree crops and woodlot exploitation. These additions form part of the growing diversification of economic strategies and material culture repertoire. They also signal an enhanced scale of production and total demand, which would have led to an overall amplification of human presence in the landscape. On the basis of our present

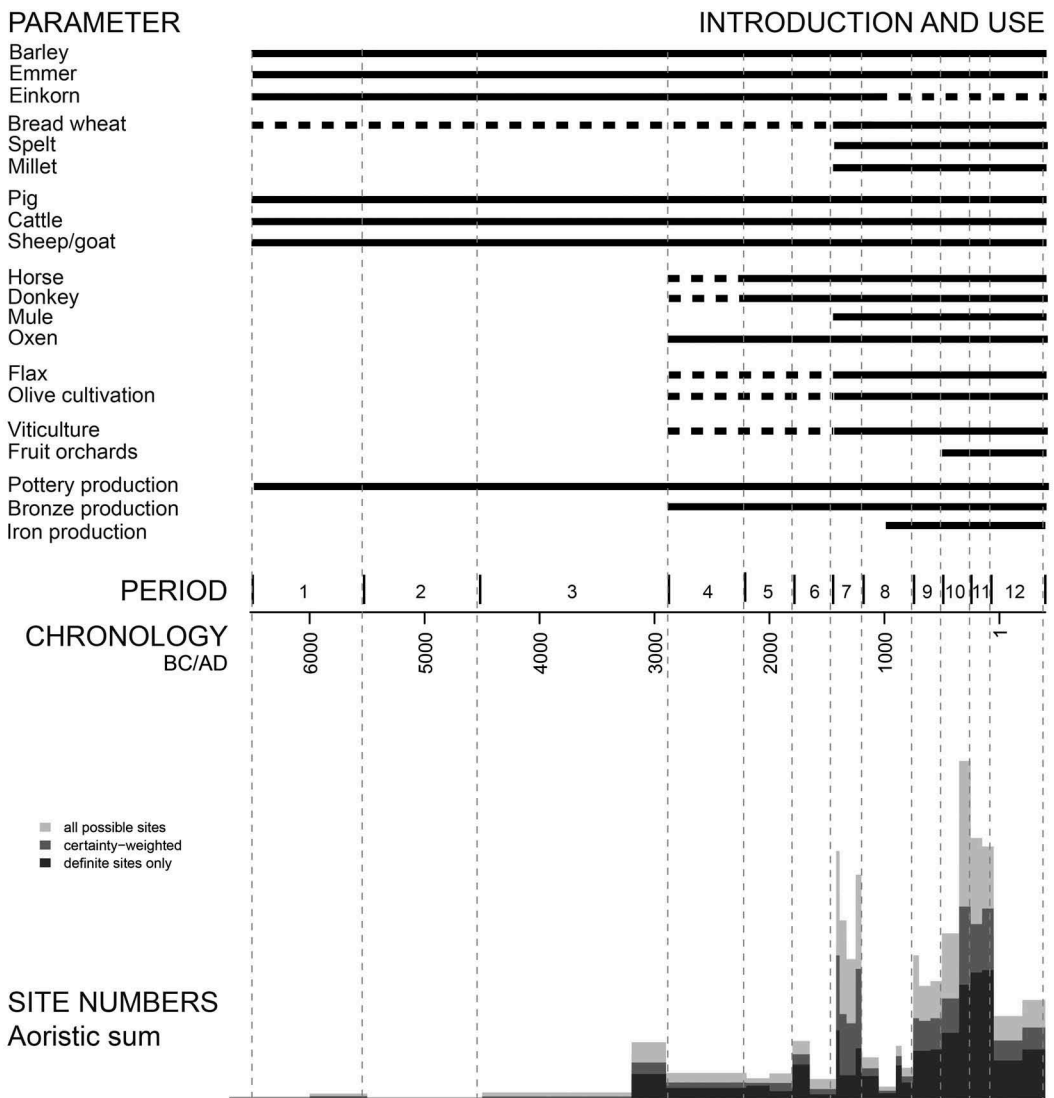


Figure 5. Visualization of the introduction and use of main land use parameters and the associated settlement data. Top: The absolute timeframe for the time of introduction of the main land use parameters dashed lines indicate low to very low visibility compared to other phases). Bottom: Fluctuations in the number of identified archaeological sites across time visualized as an aoristic sum (bottom panel) (Palmisano, Bevan, & Shennan, 2017) by which the number of sites are weighted against the duration of the period to which it has been assigned (for details see Weiberg et al., 2019).

knowledge, we cannot specify the motivations for land use change, which would have been complex and involved both internal and external processes. It is nevertheless interesting to note many new plants, animals, and industrial activities were first introduced or at least become more widespread, and therefore archaeologically detectable, during periods with high complexity and probably higher populations, possibly supporting a Boserupian view of intensification (Figure 5).

The increased usage of work animals enabled increases in agricultural production by bringing larger areas under cultivation and facilitating transport to and from the fields. The domestication of the olive as well as the spread of vineyards and orchards brought further possibilities for increased agricultural output and income from secondary products. The introduction of new field crops allowed further alternatives for more diversified agricultural strategies. Changes in per capita land use requirements from Phase 7, after which all land use parameters quantified in the present study had been introduced, derive primarily from changes in the overall scale of human activities. Notably, however, because agricultural activities make up the large majority of activities incorporated into the total land use calculations presented here, a general view of intensification does not do full justice to the complexity of ancient land use.

Ancient land use management strategies included measures relative to both the extent and intensity of land use (Meyfroidt et al., 2018). These measures could comprise intensification/disintensification, e.g. increasing/decreasing inputs and yield per hectare, expansion/contraction, i.e. variable size of the land use area, and diversification, e.g. in species composition and spatial distribution of land use (Halstead & O'Shea, 1989; Marston, 2011; Styring et al., 2017). In the preindustrial world, labor and technological limitations often also meant that increasing spatial scale led to decreased input and yield, i.e. disintensification (cf. Meyfroidt et al., 2018). In earlier phases, small-scale mixed farming, combining intensively managed gardens with small fields and limited animal husbandry, was the predominant land use form. Agricultural land use systems concentrated on localized, risk-buffering strategies, where food sources were carefully managed, and the risk of one resource failing could be compensated by another. As population size increased, and particularly when larger settlements formed, e.g. for defensive or trade specialization reasons, the increasing distance between settlements and fields made intensive forms of agricultural exploitation (e.g. manuring and weeding) increasingly impractical (Forbes, 2012a; Halstead, 2000). Carbon and nitrogen isotopes measured on cereal grains in northern Mesopotamia demonstrate a clear shift towards the expansion and disintensification of agriculture with the onset of urbanization (Styring et al., 2017, a combination referred to as extensification). In later periods, increasing populations, complex societal forms and economic specialization increased the need for larger outputs and surplus production, and an expansion of agriculture, complemented by diversification as well as cash cropping and trade. Considering the Peloponnesian material, an important regime shift in land use may be seen in the increased usage of work animals, enabling increasing productivity through larger fields. On the balance, this spatial expansion appears to be concomitant with disintensification, which leads to little overall change in our estimates of per capita land use.

In the Peloponnese, we lack the material evidence to provide more than a general view of the composition and evolution of these agricultural strategies that took place over time. Archaeological evidence confirms that Peloponnesians from the earliest periods sought to increase agricultural productivity. Manuring has recently been confirmed by stable isotope analysis of crop remains from Middle Neolithic–Late Neolithic (Phases 1–2) Kouphovouno, SE Peloponnese (Vaiglova et al., 2014). These analyses support the general assumption that manuring was a part of ancient Greek agricultural practices, likely through preferential targeting of certain crops or areas (Bintliff, Howard, & Snodgrass, 2007; Forbes, 2012a). As a complement or alternative to manuring, fields may also have been left fallow (Bresson, 2016, pp. 120–121; Moreno, 2007, pp. 19–24), a strategy often assumed for the Peloponnese (Andel, Zangger, & Demitrack, 1990; Hansen & Allen, 2011). Evidence for terracing, as a means of enhancing agricultural potential in the topographically diverse Peloponnese, is confirmed in Phase 7 (Kvapil, 2012), but may have been locally present earlier, in Phase 4 (Colaianni et al., 2012). However, the extent to which terracing was

employed in the historical period is debated (Foxhall, 1996). In addition, large-scale drainage and water management projects are recorded from Phase 7 (Hope Simpson & Hagel, 2006), augmented later by large-scale water transfer systems such as aqueducts in the Roman period (Phase 12) (Lolos, 1997). These elements were likely integral components of the agricultural system in the ancient Peloponnese but due to limitations in our understanding of their ubiquity in the landscape, and precisely how these affected crop yields and other modelled quantities, they are not currently included in our calculations. The general situation suggests, however, that intensively managed (with high manure/midden inputs) crops in the Neolithic (Phases 1–3) were gradually exchanged for, or rather complemented by, cultivation of larger areas of land from the Bronze Age (from Phase 4, and accentuated from Phase 7), probably using lower input of manure/midden, but managed instead by other resource demanding practices and work animals to increase productivity.

5.2. The role of demographic change

It has been suggested that demographic dynamics are the primary driver of land use change in history (Ellis et al., 2013; Hooke, Martín-Duque, & Pedraza, 2012). Our results support this statement, given that changes in per capita land use over time were relatively modest. While we do not directly address the total size of the Peloponnesian population size in the calculations, an assessment of the increasing size and organization of human societies in the Peloponnese across the study period shows that demographic change likely amplified the increase in calculated per capita land use (Figures 3 and 4). In the Neolithic (Phases 1–3), the Peloponnesian landscape was populated by a low number of settlements with large territories (Figure 5) (Cavanagh, 2004). This began to change in some regions with the Final Neolithic (Phase 3) and more comprehensively with the mature Early Helladic period (Phase 4) when a larger number of settlements started to occupy the landscape. Due to the long duration of Phase 4, it is difficult to fully assess the contemporaneity of these locations and it is only with the Mycenaean palatial period (Phase 7) that there is unequivocal evidence for large-scale anthropogenic transformations of the landscape (Weiberg et al., 2019). Phase 8 constitutes a break in these practices, defined by a strong decrease in the number of settlements and probably of population. Around 750 BC (onset of Phase 9) the expansion and intensification of land use took off anew and reached an unprecedented scale. Results from archaeological surveys in the Peloponnese suggest an average increase of 250% in site numbers between the prehistoric and historical periods, suggesting that population grew substantially during our period of study (Weiberg et al., 2016). Even accounting for taphonomic conditions that favor the discovery of younger archaeological material, there is no doubt that settlements in the Classical Antiquity (Phases 10–12) were generally larger and/or more numerous than those of earlier phases. While the 60% increase in calculated per capita land use we calculate from the Neolithic to the Roman period (Figures 3 and 4) seems relatively limited considering the overall differences between the societies in the beginning and the end of our study period, demographic dynamics changes the picture substantially.

When coupled with the known expansion of settlements and probably of populations across the Peloponnese, as well as increases in societal complexity, the overall scale of land use change becomes evident. Among the final three phases (Phases 10–12) that show the highest per capita land use, Phase 10 (Classical–Early Helladic) stands out as having had the largest settlements and number of confirmed archaeological sites (Figure 5), thus we may suggest that the total area under land use in the ancient Peloponnese reached its apogee during this period. Hints that population declined after Phase 10 raises interesting questions about the long-term sustainability of land use in a complex, energy-intensive ancient society. Such questions include understanding the relationship between land use and land ownership in regards to both cash cropping and subsistence farming in this period. The impact of environmental dynamics on demography and the spatial configuration of land use also needs to be better understood. Future studies should attempt to improve our understanding of population levels and demographic change in the Peloponnese, perhaps by combining site-survey data with statistical methods using radio-carbon date frequencies (Bevan et al., 2017; Weiberg et al., 2019).

5.3. Impacts on the environment and implications for long-term sustainability of land use systems

Following the definition of sustainability as '[a] dynamic process that guarantees the persistence of natural and human systems in an equitable manner' (IPCC, 2014), it appears that ancient Peloponnesian land use systems were never wholly unsustainable. Although political structures and the level of societal complexity changed over time, a combination of dry farming and animal husbandry remained the core of the economy throughout the studied period, as is outlined in [Figures 3–4](#). On the other hand, ancient land use systems were never wholly sustainable. Instances of increased sedimentation rates as early as the Early Neolithic (Phase 1) (Fuchs, 2007), suggest that land use did have a local impact on the environment both on short and relatively long time scales. As suggested also by enhanced levels of anthropogenic pollen indicators in certain periods and places, land use did have an influence on vegetation from the early phases, but similar to many other Mediterranean regions, human activities did not have a lasting effect (impact) on overall vegetation until the Bronze Age (Mercuri et al., 2019; Weiberg et al., 2019). It is also in the Bronze Age that the first major societal expansion episodes occur (at 2900 BC, Phase 4 and 1400 BC, Phase 7), coupled with increased socio-political complexity, followed by processes of socio-economic disintegration a number of centuries later (around 2200 BC and 1200 BC). Phase 7 (Late Helladic III, i.e. the Mycenaean palatial period) especially, can also be connected to the greatest diversification of the Peloponnesian land use components, with the increased use of auxiliary animals and addition of new crops ([Figure 5](#)), possibly to maximize output for a growing population (Finné et al., 2017; Halstead, 2000, 2001; Weiberg & Finné, 2018). These attempts towards maximization may in turn have decreased societal resilience during a time of climate change potentially leading to decreased agricultural output during the final phase of the period, and ultimately likely contributed to the disintegration of the Mycenaean politico-economic system around 1200 BC (Knapp & Manning, 2016; Middleton, 2010; Weiberg & Finné, 2013). During the final two generations or so of the Mycenaean palatial system, the economy must have been stretched close to its limits, given the size and number of sites located in the landscape and the sheer monumentality of some of the palatial endeavors that required a great toll of both natural and human resources (Finné et al., 2017; Maran, 2009).

Based on the average assessments of the present study, it seems unlikely that prehistoric population levels surpassed the carrying capacity of any one region even if the strain may have been greater in some areas such as in those regions dominated by the Mycenaean palaces (Phase 7). With strongly increasing site numbers and likely accelerating population growth after ~700 BC (from Phase 9), however, it is likely that land shortages developed at least in some regions and at certain times. A case in point can perhaps be the communities of Southern Argolid, in the northeast Peloponnese. The area was covered by an archaeological survey in the 1980's and the identified settlements of the Classical-Hellenistic period was estimated to correspond to a population of approximately 11,000 inhabitants within the surveyed area (206 km², i.e. 20,600 ha) (Jameson, Runnels, & Van Andel, 1994). Such estimations of absolute population numbers from surveys are problematic (Osborne, 2004), and should be treated with caution. It is interesting to note, however, that the surveyed area, following our present estimations and assuming that all land within the surveyed area was useful for one or several of the land use types included in our assessments, could harbor only a population of roughly 7000 inhabitants (a spatial requirement of ~3 ha per capita). A larger population is likely to have created deficits of land and constituted a threat to food security. Given that a larger population is estimated, it seems reasonable that two of the communities from within the surveyed area were among the recipients of relief grain from Cyrene, modern Libya, in the 4th century BC (Bresson, 2011; Jameson et al., 1994).

6. Conclusions

In this study we assembled data from a variety of sources in a first attempt towards a synthetic view of long-term changes in the land footprint of Peloponnesian societies. Our results suggest that the spatial requirements of land use ranged from 2.4 ha per capita in the Early Neolithic–

Middle Neolithic (Phase 1, with the lowest value of 2.0 ha in the Final Neolithic–Early Helladic I, Phase 3) to 3.2 ha per capita in the Classical–Early Hellenistic to Late Hellenistic period (Phases 10–11). The increase in per capita land use is primarily the result of the introduction of new animals, plants and agricultural techniques to the set of land use strategies established in the Neolithic. Woodlot exploitation and tree crops display the highest increase over time, though the total land use area needed for these activities would always have been limited compared to crop- and pasture-land. Pasturage consistently resulted in the highest demand for land, with changes primarily related to secondary products and expanded use of work animals. Change in land requirements for field crop cultivation were modest over time, but the category comprised just over one third of total land requirements in any period.

Importantly, estimations of land use of this kind represent a highly idealized and generalized representation of the spatial requirements given certain land use systems, and should not be placed on a map to represent reality. Our calculations represent estimations of the typical, or average, amount of land required for household subsistence needs, requirements that in reality could have been both larger and smaller, depending on local characteristics of the physical environment and socio-cultural system. Both climate and soils vary naturally across the landscapes of the Peloponnese and there are many different management strategies that could be employed to enhance the use and/or output, and thus decrease the per capita spatial requirements. Many of the separately prescribed land usages, and hence spatial needs, could have been shared between activities, with sheep and goats having complimentary dietary preferences and consuming different types of plants on the same lands, possibly grazing fallow lands as well as agricultural lands for part of the year, and with olive trees grown along the border between cultivated fields or fully incorporated with other crops.

Assessments of the actual *effects* of land use rely on the contextualization of the land use system. The demographic factor is highlighted as crucial for understanding the total amount of land under use at any given time. Based on archaeological evidence of demographic change, we hypothesize that the period of greatest overall land use in the Peloponnese occurred during Phase 10 (Classical–Early Helladic), even though per capita land use remained largely the same during the following two phases (11 and 12). An important aim for our study was to provide a new basis for modelling past land use that is anchored in observations, rather than the back-extrapolations (Klein Goldewijk et al., 2017) and empirical relationships (Kaplan et al., 2009) that are currently the state-of-the-art in large-scale land use reconstructions. Unfortunately, the chronological resolution of our records is not fine enough to determine precisely when new crops, animals or technologies were introduced, nor to fully reconstruct the motivation behind their introduction. We are further not capable of making a perfect reconstruction of land use in ancient landscapes, being limited by what is archaeologically detachable and available through ancient texts, particularly in terms of the organization of labor and the importance of non-subsistence activities, e.g. cultural and religious, on land use. Nevertheless, by calculating the land needed for human subsistence in terms of food, fuel and material culture, we can begin to quantify the importance of sociocultural attributes in influencing the changing imprint of humans on the landscape over time, at least in terms of a lower bound estimate.

Our results provide a valuable data set for evaluating middle-range theories of land use change, particularly over the *longue durée*. For example, while Boserupian intensification triggered by demographic growth may have occurred in certain times and places in the Peloponnese, overall we do not see evidence of substantial decreases in per capita land use at any time during the seven millennia of our study period. Our results instead seem to lend support to scenarios of gradual increases in per capita land use over much of preindustrial time that must have been followed by intensification only very late in the Holocene, perhaps only in the industrial era (Ruddiman & Ellis, 2009). Interestingly, this phenomenon may be observed empirically for Western Europe in the KK10 scenario (see Figure 2 in Kaplan et al., 2011).

Our results are further valuable for archaeology, allowing comparative analyses of long-term land use, and for current debates on sustainability, for which lessons from the past are starting to be increasingly viewed as useful (Costanza et al., 2012; Dearing, Braimoh, Reenberg, Turner, & van der

Leeuw, 2010; Schoon, Fabricius, Anderies, & Nelson, 2011). New integrative tools, including the model and parameters presented here, may help data producers format commonly disparate archaeological and historical records in a way that facilitates their relevance for quantitative models of human-environment interactions and their incorporation therein (Morrison et al., 2018). We hope that these efforts may result in an improvement of large-scale scenarios of preindustrial anthropogenic land cover change widely employed by earth system scientists (e.g. Harrison et al., 2018; Kaplan et al., 2011). Finally, the results of our study hold the promise of being improved in the future, as new archaeological, historical, and paleoenvironmental evidence emerges, which will further advance integrated and comparative discussions regarding land use and the impact of land use in ancient Peloponnese.

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