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LETTER

Land use patterns and climate change—a modeled scenario of the Late Bronze Age in Southern Greece

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Abstract

In this study, we present a modeling approach that investigates how much cultivable land was required to supply a society and whether societies were in need when environmental conditions deteriorated. The approach is implemented for the North-Eastern Peloponnese and is based upon the location of Late Helladic IIIB (1300–1200 BCE) archaeological sites, an assessment of their sizes, and a proposed diet of the people. Based on these information, the areal requirement of each site is calculated and mapped. The results show that large sites do not have sufficient space in their surroundings in order to supply themselves with the required food resources and thus they depended on supplies from the hinterland. Dry climatic conditions aggravate the situation. This indicates that potential societal crisis are less a factor of changing environmental conditions or a shortage of arable land but primarily caused by socio-economic factors.

1. Introduction

To which degree are societies impacted by climate change? An age-old question that gained new relevance in the so called Anthropocene and the ongoing global environmental change (see Lewis and Maslin 2015, Haraway 2015, Ruddiman 2017). Archaeological examples derive from all parts of the globe, such as Mesoamerica, Greenland, the Indus valley and Cambodia (see Weiss 2017, Middleton 2017b). By investigating past societal dynamics, in the present case that of the Peloponnese peninsula in Southern Greece during the 2nd millennium BCE, we can derive narratives and heuristics that might enrich the current debates on (a) resilience, vulnerability, and collapse, as well as (b) the causes of the breakdown of Mycenaean palace economy (see Middleton 2012, 2017a, and references therein).

The Peloponnese peninsula has been the home of farming communities since the beginning of the 7th millennium BCE (see Bintliff 2012). Most well-known during prehistory is the Mycenaean palatial period (ca. 1400–1200 BCE), during which Mycenaean ways of life became dominant in the Aegean area until the Mycenaean palace economies came, rather abruptly, to an end. The reasons for this breakdown have been massively debated (see Middleton 2010, Cline 2014, Finné *et al* 2017, and references therein). The possible impact of climate change on these sequences of events has long been an issue (for a historical overview see Knapp and Manning 2016) but one that has come increasingly to the fore in the advent of local paleoclimate records (Drake 2012, Knapp and Manning 2016, Finné *et al* 2017). The end of the palatial period coincides with a period of arid climate (the so called 3.2ka event) and can be chronologically connected to societal transformations throughout the Eastern Mediterranean region (Roberts *et al* 2011, Langgut *et al* 2013, Wiener 2014, Kaniewski *et al* 2015). The question is how much influence should be ascribed to

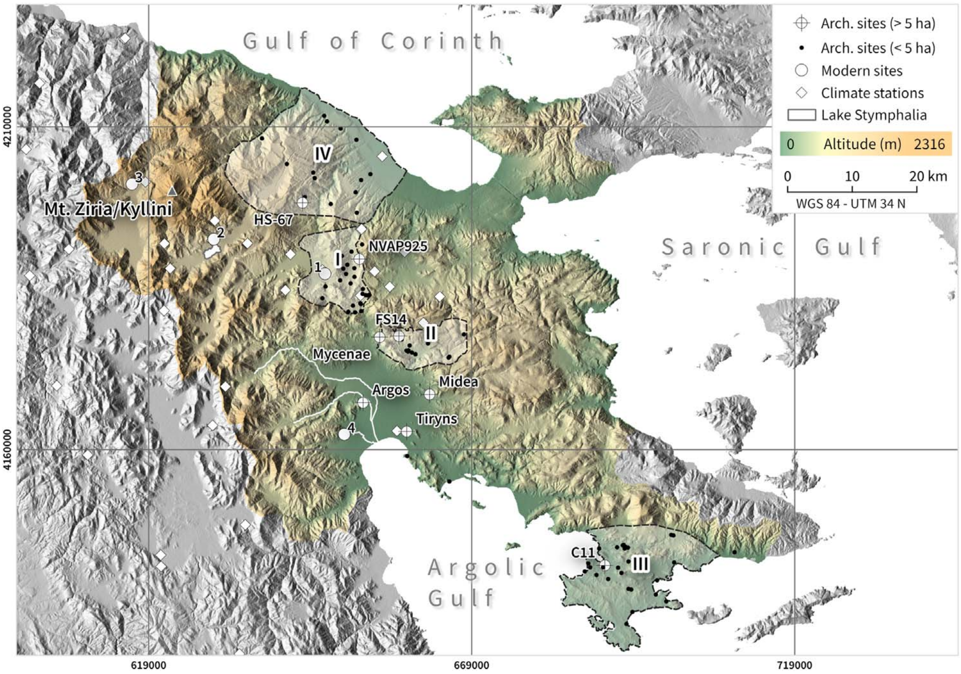

Figure 1. Overview of the research area in the North-East Peloponnese with Late Helladic III archaeological sites (sites larger 5 ha are named). Roman letters indicate survey regions: (I) Nemea Valley intensive survey; (II) Berbati-Limnes intensive survey; (III) Southern Argolid intensive survey; (IV) Sikyon extensive survey. Tiryns, Midea, and Argos belong to the Argive plain survey. Modern sites: (1) Nemea; (2) Stymphalia; (3) Pheneos; (4) Kefalari.

climate, and how the balance between climate and internal socio-economic or other factors should be understood (Middleton 2017a, Weiberg and Finné 2018).

One conceptual framework to address this issue and related questions of human-environmental interaction revolves around the concept of resilience, the adaptive cycle, and socio-ecological systems thinking (see Folke 2006, Smit and Wandel 2006, Bollig 2014, Bradtmöller *et al* 2017). Such frameworks allow grand narratives of societies and their dynamics to be drawn (e.g. Weiberg and Finné 2018, for the region of this study). Here, we offer a complementary view that focus specifically on issues of vulnerability. We follow Adger (2006, 268) who understands vulnerability as loose antonym of resilience and defines it as '(...) the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt' (see also Adger 2000). This exposure can be objective and subjective (see Christmann and Ibert 2012) and is often related to the way a society is internally structured, when exposed to external stresses (see De Keyzer 2016).

Such considerations, linking external drivers and internal societal structure, are intrinsic to recent frameworks for vulnerability assessments (e.g. Kok *et al* 2016, Nelson *et al* 2016). The social conditions commonly relate to aspects of human well-being, connectedness and mobility, as well as to population dynamics. Here, we primarily aim for what Nelson *et al* (2016) define as 'population-resource conditions', and specifically the availability of food, where the pressure of resources can be calculated by setting estimates of population density against the spatial needs for sustenance. The motivation is that the balance between resources and population numbers reduces the risk of shortfalls and thereby increases food security.

In this study, we present an approach that investigates (a) to which degree locally available resources were exploited in order to meet the needs for a society's annual sustenance and (b) whether these were deficient when environmental conditions changed. The approach is tested on the north-eastern Peloponnese peninsula during the Late Helladic IIIB period (ca. 1300–1200 BCE). Based on the location and size of the archaeological sites, as well as the proposed diet of the people, the areal requirement of each settlement with its annual sustenance demands is calculated and mapped.

2. Study area

2.1. Geographical setting

Geomorphologically, the Peloponnese peninsula (21 550 km^2) in Southern Greece is characterized by a mountainous relief and including strong altitudinal gradients on relatively short distances. The highest mountains reach altitudes of more than 2400 m above sea level, only few kilometers away from the coast—e.g. the highest peak of the study area, Mt. Ziria/Kyllini (2374 m), is situated only 20 km away from the coast of the Gulf of Corinth (figure 1).

Limestones and carbonate rich conglomerates dominate the geology of the study area (Morfis and Zojer 1986). Most of the limestones are strongly karstified, which becomes apparent i.a. in typical geomorphological, hydrological features such as large flat plains (poljes). The largest poljes in the study area, Pheneos, Stymphalia and Phlious/Nemea, which surround the limestone massif of Mt. Ziria have an area extent between 30 and 50 km^2. Depending on the prevailing climate conditions and the human impact on the drainage system at different periods, these plains were covered by large lakes. Substantial water management practices in the study area are known at least since the Late Bronze Age, like the Late Helladic IIIB dam near Tiryns from around 1300 BCE (Zangger 1994). At the turn of the 19th to 20th century CE, most of the poljes were artificially drained to obtain more flat areas for agricultural use, with Lake Stymphalia remaining the only lake that survived until present. Many slopes in the area show signs of agricultural terracing, in some places even in altitudes above 1500 m. However, neither the age of the terraces nor what was cultivated on them is known (an exception are the terraces of Kalamianos, see Kvapil 2012).

The karst waters draining from the mountains and poljes in the west of the study area supply huge springs (e.g. Lerna, Kiveri, Kefalari) in the Argive Plain, which today covers approx. 150 km^2 at the north-eastern coast of the Peloponnese. The river Erasinos, issuing from the spring at Kefalari, formed Lake Lerna at the coast south of Argos, which existed at least during a period from approx. 4800 BCE until 800 CE (Jahns 1993, Zangger 1993, Katrantsiotis *et al* 2019).

The area is characterized by a warm temperate climate with hot and dry summers (Csa after Köppen and Geiger; Kottek *et al* 2006). Data from meteorological stations on the peninsula shows that the annual rainfall exceeds the critical 250 mm isohyet—that is essential for rain-fed agriculture (see Bruins *et al* 1986)—everywhere with a decreasing trend towards the east. Following Finné *et al* (2017) and Weiberg and Finné (2018) the climate during the period in question shows a dry episode of some 20 years at 1250 BCE (±30 yrs), but otherwise generally 'wet' conditions, although probably more volatile than during the previous century. Only after 1200/1170 BCE does a trend towards severely arid conditions set in, with increasingly dry conditions until around 1050 BCE.

2.2. Archaeological setting

Around 1200 BCE, after two centuries of Mycenaean dominance in the Aegean world, the palaces at Mycenae, Tiryns, Midea, Thebes, and other former centers were destroyed and not re-built (Dickinson 2006, Maran 2006, Deger-Jalkotzy 2008). For about a century, certain citadels (e.g. Tiryns in the Argolid, Teichos Dymaion in Achaea) witnessed continued activities; these were taking place, however, on a much smaller scale than before and supposedly not under the lead of a palatial authority (maybe with a short-term exception at Tiryns, see Maran 2006).

During the palatial period, the NE Peloponnese was densely populated with a hierarchy of settlements spread throughout the landscape, on the plains, and in the uplands. It is proposed that Mycenae exercised some control over large parts of NE Peloponnese, and hence dominated other palatial centers in the region (Bennet 2013). The Mycenaean polities (see Drake 2012) were dependent on a secure supply from their agricultural economic system, the basis of which were field crop cultivation (barley, einkorn, and emmer, but diversified during Mycenaean times to include also free-threshing wheat, millet, and spelt) and animal husbandry (goat/sheep, pigs, and cattle; Weiberg *et al* 2019, with references).

3. Methods

Our methodological approach is to calculate the areal requirements for selected archaeological sites. Environmental suitability mapping is combined with a population and diet based nutrient requirement calculation to arrive at a measure of spatial needs for different land use practices per settlement. This allows to assess for which sites the available space was sufficient. We expand the approach by adjusting the suitability mapping to reflect drier climatic conditions.

3.1. Archaeological information

In the present study, only dietary needs are modeled, and the results therefore indicate the minimum needs of the settlements. The prescribed diet is based on estimations by Weiberg *et al* (2019) and is cereal based, complemented primarily by legumes, fruits and nuts, dairy, and only a limited amount of meat (see supplemental material 1 available online at stacks.iop.org/ERL/14/125003/mmedia). Our modeling approach uses settlement data for the second half of the palatial period (Late Helladic IIIB period: ca. 1300–1200 BCE), derived from three regions covered by differently intensive archaeological surveys (Wright *et al* 1990, Jameson *et al* 1994, Wells and Runnels 1996, Lolos 2011, Cloke 2016, see supplemental material 2. No such data exists for the Argive Plain and for this region we have thus used population estimates for the main settlements only. The population of the Argive Plain has been estimated to around 20 000 inhabitants, of which Mycenae, the largest settlement in the region, held around 6400 inhabitants (Bennet 2013, Bintliff 2016). It should be noted, however, that all population estimates are inherently uncertain (see Osborne 2004). They are generally generated from estimations of settlements sizes, more readily identified in excavated areas than from surface reconnaissance. Hectare values for excavated sites are hence

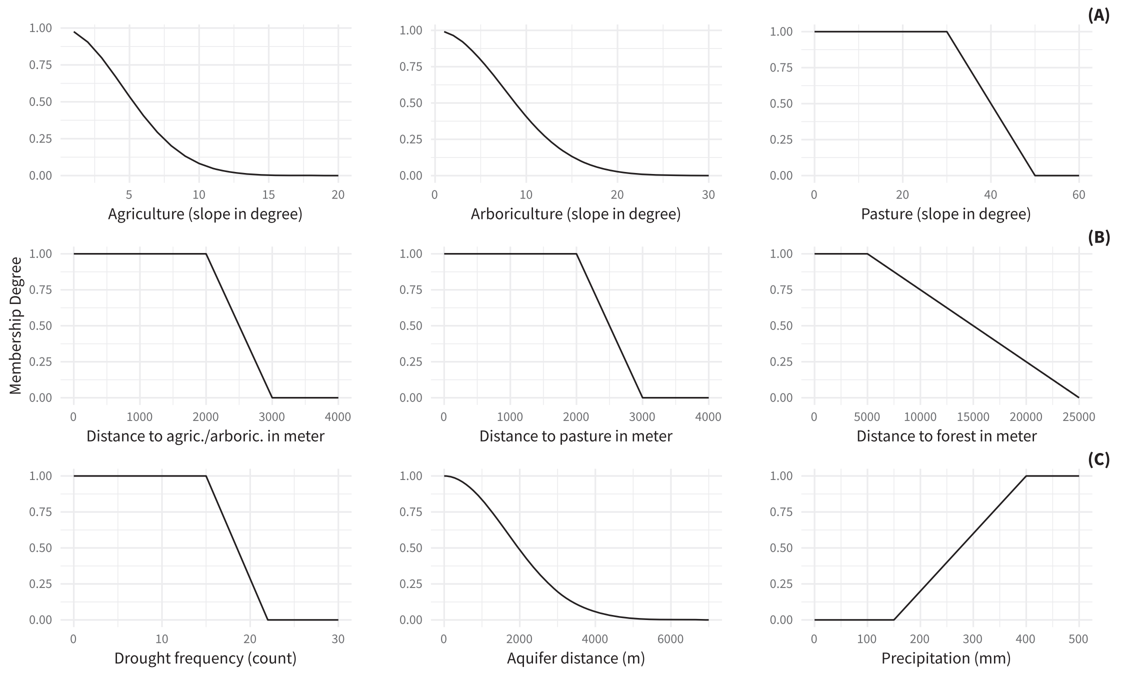

Figure 2. Fuzzy sets as employed in the study. Each sets represents the suitability/favorability for the individual parameter raster.

more secure, but even excavations do very rarely cover the full extent of the original settlement in one specific phase. To allow for these uncertainties, we have incorporated three population scenarios, calculating 100, 150, and 200 inhabitants per hectare.

3.2. Land use suitability

The assessment of the environmental suitability for land use activities (i.e. agriculture, arboriculture, pasture, and wood) is based on the integration of expert-knowledge on land use practices with empirical data on environmental characteristics. Both are combined in a fuzzy rule-based system. Fuzzy logic allows to exemplify our assumptions by stating them as linguistic variables (Zadeh 1965). Furthermore, using fuzzy in place of crisp sets helps to classify data where clear borders are hard to establish. Fuzzy methodology is used in different contexts in (landscape) archaeology; examples range from site location analysis (Jasiewicz 2009, Popa and Knitter 2015), over viewshed methods (Loots *et al* 1999), to chronology (Nakoinz 2012). We employ the R package FuzzyLandscapes (Hamer and Knitter 2018), inspired by Jasiewicz (2011), to analyze a raster based fuzzy rule-based system.

Different raw data were employed: information on slope in degrees is derived from the European Digital Elevation Model (EU Copernicus programme 2016, version 1.1), via GRASS GIS (GRASS Development Team 2017). Information on precipitation are provided by the Greek Special Secretariat for Water and is derived from 68 climate stations located on the Peloponnese. These data are interpolated using multiple linear regression and the independent parameter latitude, longitude, and elevation. Calculations are conducted using R (Core Team 2019) and the packages dplyr (Wickham *et al* 2019) and raster (Hijmans 2019). The construction of wells requires suitable geological conditions, in particular highly productive porous or fissured aquifers. These information are derived from International Hydrogeological Map of Europe 1:1500 000 (BGR *et al* 2008). Soils of very high to medium productivity on the Peloponnese—i.e. Fluvisols, Cambisols, Calcisols, and Luvisols (according to Yassoglou *et al* 2017)—were accessed from SoildGrids250m, a Global 3D Soil Information System, provided by ISRIC World Soil Information (further information on SoildGrids and the corresponding methodology to create the grids is given by Hengl *et al* 2017). To reduce computation time, all calculations are conducted with a spatial resolution of 75 by 75 m.

Following Hughes *et al* (2018), we distinguish between four different categories of land use, for which suitability maps are created based on the following assumptions:

- *Agriculture*, i.e. cereals and legumes, are considered to grow (a) on areas with little to no slope induced erosion (figure 2(A)), (b) in areas with sufficient rainfall for rainfed agriculture (figure 2(C)), (c) on fertile soils (according to Yassoglou *et al* 2017, 24f.), and (d) in areas with easy access to groundwater resources (figure 2(C)). Terrace farming is not considered here, since it would introduce another level of eco-social complexity. Not considering terraces leads to an underestimation of available land. However, an appropriate representation of

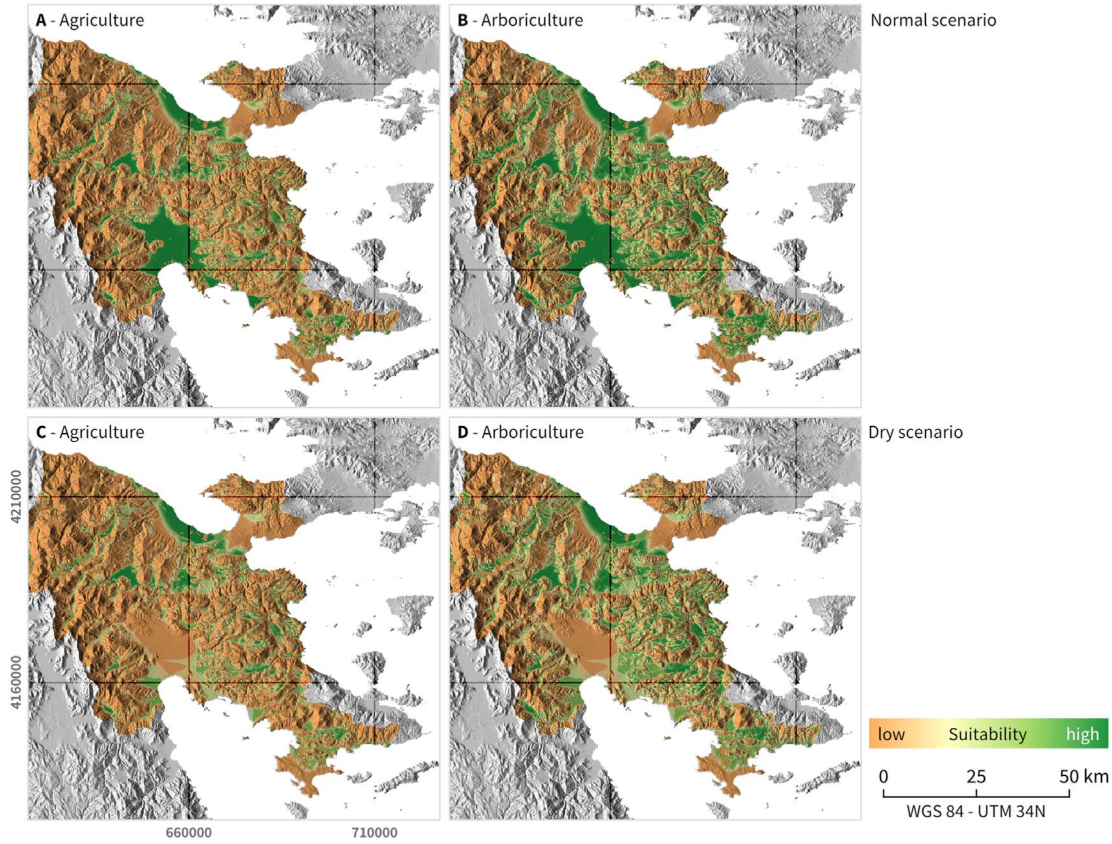

Figure 3. Slope, soil, and groundwater determined suitability for agriculture under normal (A/B) and under the employed dry scenario (C/D) mirroring more arid, unstable conditions.

terraces also necessitates extended assumptions on nutrient requirements for which we are lacking empirical data. The same holds true for water-management techniques utilized for irrigating the fields. These are likewise not considered.

- *Arboriculture*, i.e. the cultivation of fruit trees, nuts, olives, as well as vine, has the same requirements as crops, however, the slope is less restrictive (figure 2(A)).
- *Pasture*: Pastoral activities are only restricted by very steep slopes, following the assumption that these areas are too steep to have vegetation (figure 2(A)).
- *Wood*: Forest could potentially grow everywhere (see Beuermann 1956).

Agriculture and arboriculture are labor intensive. Accordingly, the suitability maps are combined with shortest walking distances to archaeological sites (calculated using GRASS GIS; GRASS Development Team 2017): suitable areas that are more than 2 km distant from a site decrease in suitability until the areas are treated as unsuitable at distances larger than 3 km (2.5 km commonly used for agricultural societies; Flannery 1976, Bintliff 2012, Farinetti 2016, Bonnier *et al* 2019). Pasturage is less labor intensive hence the determining distance for pastoral activities is 5 and 6 km. Wood resources are increasingly difficult to acquire after 5 km distance from a site (figure 2(B)).

3.3. Area requirement assessment

The calculation of the areal requirements per site is an extended version of the approach presented by Hughes *et al* (2018), implemented in the R package LandUseQuantifieR (Knitter *et al* 2019). It is based on assumptions about the general nutrient, i.e. kilocalorie (kcal) as well as protein requirements of an individual with an active lifestyle and information on population size (for further details and exact empirical values see Knitter *et al* 2019). These values are combined with the data on diet characteristics (see supplemental material 1) and information on the nutrient density of plants and animals (for exact empirical data see Knitter *et al* 2019) in order to assess the minimum area that is required to fulfill the calorie and protein needs of the population.

The calculated areal demands are mapped in relation to the modeled suitability of the area: each grid cell has a certain suitability for agriculture, arboriculture, pasture, and wood (see section 3.2). The algorithm for the distribution of these area requirements is based on a combination of the shortest walking distance to archaeological sites and the Euclidean Norm —the square root of the sum of squares of the distances in each dimension—of suitability for the

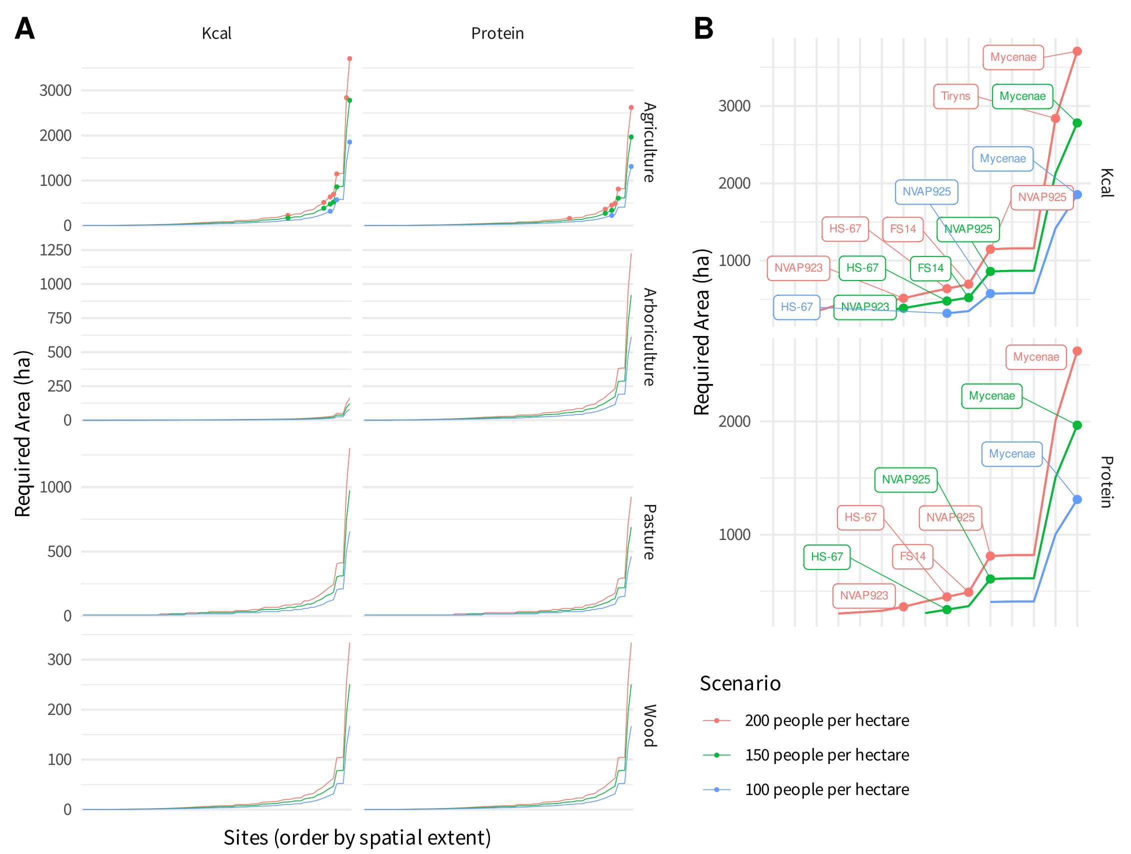

Figure 4. Required area per land use category and site during normal conditions under different scenarios. (A) for all sites; sites whose required area exceeds the available area are marked with a dot and are shown in detail in (B); (B) Sites whose required area to grow crops exceeds the available area are labeled. Names correspond to the archaeological nomenclature.

different land uses. The assignment of land use to the individual pixels is done in an iterative process. The initial value for the iteration equals the Euclidean Norm of the maximal suitability value of a land use category that has minimal distance to an archaeological site. The iteration runs through all cells, ordered consecutively from smallest to largest distance. In each step, the land use category with the largest quotient, i.e. LU_k, is assigned to the cell base upon:

$$LU_k = \max\left(\frac{E_{k,0..i}}{E_{k,0..i-1}}\right),$$

where E is the Euclidean Norm, k is the land use category (i.e. agriculture, arboriculture, pasture, or wood), $0..i$ are all as k categorized cells including the current cell, and $0..i-1$ are all hitherto as k categorized cells.

3.4. Changing environmental conditions

In order to test the effects of dry climatic conditions during the Late Helladic IIIB period (see Finné *et al* 2017, Weiberg and Finné 2018), we employ modern climate station information and relate them to the standardized precipitation-evapotranspiration index (SPEI, McKee *et al* 1993). The idea is based on the study of Beckers and Schütt (2013) and assumes that general atmospheric dynamics are similar between today and the period under study. The R package SPEI (Beguería and Vicente-Serrano 2017) is employed to calculate SPEI values. Since the index is related to the general precipitation record, negative values indicate times where less precipitation occurs than expected. Accordingly, it can be translated to be a measure of the strength of rainfall variability. Droughts impact the ability to conduct rain fed agriculture. Thus, areas with generally lower precipitation values are more vulnerable to variable rainfall than other areas.

The SPEI is calculated for each year between 1970 and 2000 for a data set of 68 climate stations on the Peloponnese. Subsequently, the SPEI values of the individual stations are interpolated using multiple linear regression with the independent variables latitude, longitude, and elevation. Based on this an areal representation of SPEI for the Peloponnese for each year is achieved. Afterwards the drought maps were summed up to arrive at a drought frequency map for the area. If there were more than 15 droughts, i.e. in more than 50% of the cases in the recorded period, we regarded this area as increasingly unsuitable for rain-fed agricultural purposes (figure 2). Note that the findings have to be treated with caution, since the utilized time series is rather short and its dynamics might not be similar to earlier periods.

Based on this analysis, it gets obvious that drought conditions are heterogeneously distributed

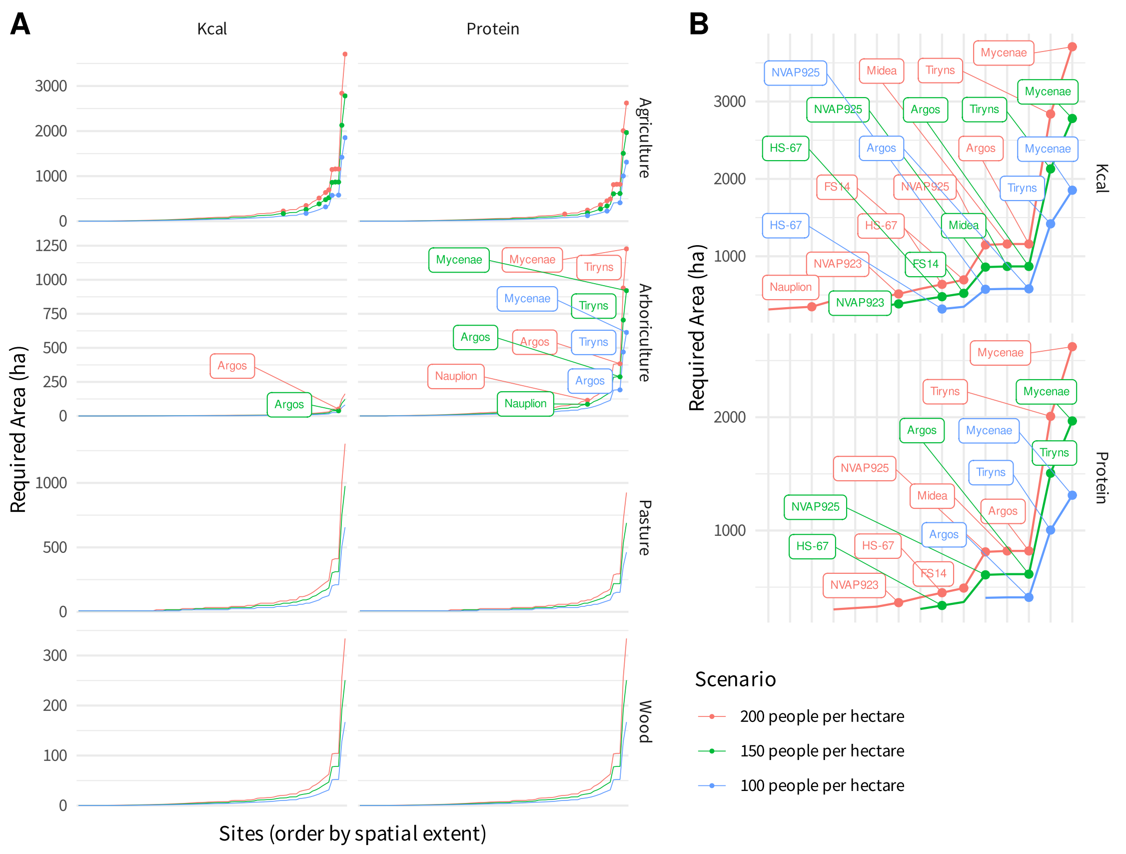

Figure 5. Required area per land use category and site during dry conditions under different scenarios. (A) for all sites; sites whose required area exceeds the available area are marked with a dot and are shown in detail in (B); (B) Sites whose required area to grow crops exceeds the available area are labeled. Names correspond to the archaeological nomenclature.

throughout the study region, threatening sustainable rainfed agriculture (see figure 3). This threat to experience a drought is implemented as scenario by integrating it as fuzzy variable to the suitability for agriculture, arboriculture, and pasture: the higher the risk of droughts, the lower the suitability of an area for these land use practices (figure 2(C)).

4. Results

Small to medium sites (approx. < 3 ha) have sufficient space to fulfill their caloric or protein requirements (figure 4(A)). This is also the case under dry climatic conditions (figure 5(A)). Only regarding crops, the largest sites (approx. > 3 ha) do not have sufficient space for agricultural purposes (figure 4(B)). This pattern aggravates during the dry scenario, during which also the space to produce arboriculture products is insufficient (figure 5(B)). The deficit of sufficient space, as recorded for larger sites, is independent of the assumed population scenario. Arboriculture and pasture show an opposing trend with marked difference in required area between protein and kcal (compare figures 4(A) and 5(A)). Especially the variation in areal requirements for arboriculture between the kcal-based and the protein-based scenario is considerable.

The mapping of land use areas shows a similar pattern for small sites (figures 6(A) and (B)) while in the Argive plain that is characterized notably by large sites, differences between the two scenarios are discernible (figure 6(C)). Besides, the effect of input data—especially the interpolated droughts, as well as the integrated settlement-distance—becomes obvious as artificial looking rings or stripes in the plain. The unused areas in the northern part of the Argive plain are related to the distance constraint, i.e. those areas are too far apart from one of the prescribed settlements to be used for agricultural practices.

5. Discussion

The results show some artifacts that are related to selected methods and input data. For instance, the drought scenario, due to low data density, leads to unrealistically sharp-edged boundaries. More data or a different interpolation method could improve the results. However, since the scenario-approach itself follows simplifying assumptions, further data-tweaking might cause an overconfidence in the result that is not backed by input data or proxy information. Furthermore, decisions during the creation of the model (e.g. constraining distances for land use practices or the assumption that people will conduct

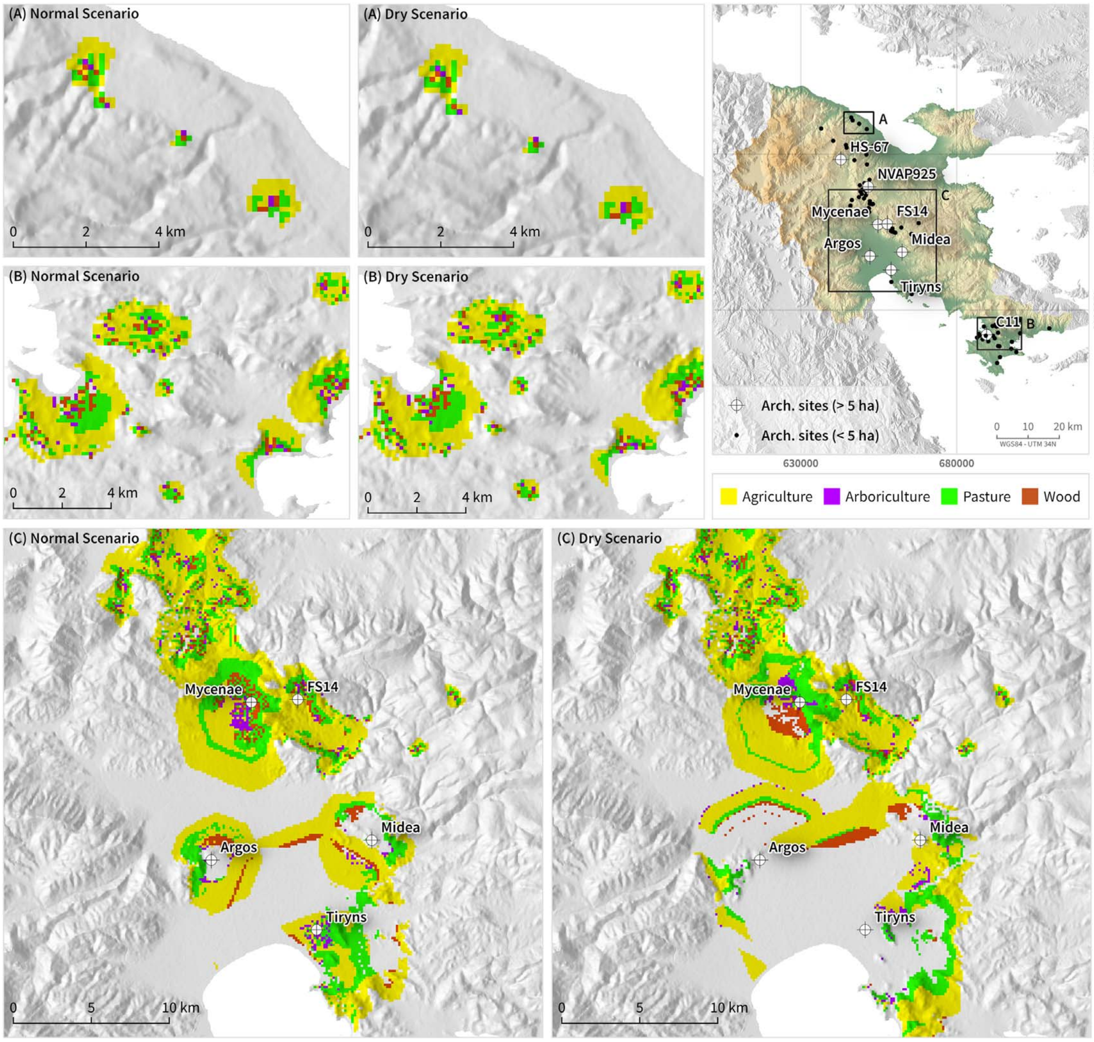

Figure 6. Modeled areas for different land use practices. Since the spatial demands between the different population scenarios does not change significantly only the 200 people per hectare model run is shown.

activities as close as possible to their homes) and definitions of fuzzy sets have a strong influence on the modeled results. Accordingly, less conservative values, e.g. regarding slope or size of the agricultural hinterland, might lead to different interpretations. However, since the chosen values are based on empirical studies the results can be regarded as reasonable estimates.

The differences in areal requirements when considering calories or protein as nutrient base are apparent. This highlights the importance of the utilized land use technique and the assumed diet. It has to be analyzed in more detail in future studies on nutrient requirements, diet structure, and cooking habits of different parts of society, as outlined, e.g. by ancient authors like Galen (see Grant 2000). Furthermore, in the current version of the model yields are reflected only by one productivity measure. Manuring, soil conditions, harvest time, or weather conditions are all aspects that determine the eventual yield of a crop. Due to the lack of empirical information and our decision to have a simple model with as little as possible complicating extra assumptions, the mentioned yield influencing elements are not integrated. This again highlights the fact that not the resulting values itself but the general pattern should be considered when drawing conclusions.

Besides these limitations, the results show that large sites do not have sufficient space in their surroundings in order to supply themselves with the required food resources. This confirms the suggestion that the large sites were always dependent on external food supplies (e.g. Halstead 1999, Bintliff 2016). This holds true for the normal scenario as well as for a scenario of dry climatic conditions indicating thus, that a potential societal crisis is less a factor of changing environmental conditions or a shortage of arable land but rather caused by socio-economic factors.

Climate, however, may have been an aggravating factor, adding to a socially produced vulnerability. The content of direct control from the palaces on the surrounding regions and lower-order settlements is still debated but is generally assumed to include primarily resources needed for palace-controlled production, for local use and for exchange (Foxhall 1995).

Incoming grain listed by palace administrators appear primarily not as provisions for the daily diet of palace inhabitants, but as rations for workers, for sacrifice, and for feasting (Bennet 2013). Large scale feasting events were one strategy for the palatial elites to build cohesion and loyalty and to uphold authority. Extended possibilities for grain storage within palace boundaries during the Late Helladic IIIB (ca. 1300–1200 BCE) at Mycenae—also known from Pylos in Messenia—may have been a way to secure such activities (Whitelaw 2001, Maran 2009). Another way for palatial elites to make themselves essential beyond their peers may have been to provide food-security in case of shortfalls, due to droughts or other factors (Foxhall 1995, Finné *et al* 2017). Some movement of grain from external entities to the palaces was thus already part of the Mycenaean palatial system, through taxation, exchange and/or agricultural partnerships (e.g. Halstead 1999). If, however, the palaces and other major settlements experienced additional food deficiencies, as modelled in the dry scenario, this may have compromised their authority and the overall cohesion in the region. If smaller settlements could produce what they needed, they were in a position to provide relief food. Whether such relief was provided by free will or by coercion, such a relationship could have affected the power balance in the region. An imbalance would have added to the overall vulnerability of the Mycenaean polities, a vulnerability that was likely already high due to a stretched economy, including largescale building projects and perhaps generally turbulent times within the Eastern Mediterranean trade- and contact networks important to the Mycenaean elites (Bennet 2013, Weiberg and Finné 2018).

6. Conclusions

The fuzzy suitability modeling helps to create contextualized and spatially constrained information on the general subsistence patterns of an area. This updated modeling method showed that area requirements are a function of scale: small sites are not affected by a need for space even under worse climatic conditions; on the contrary, large sites are always affected. Accordingly, a functioning socio-economic and socio-ecological system, organizing production and exchange, was a prerequisite to sustain the largest Mycenaean settlements. In the Late Helladic IIIB context, such a reliance of the palaces on external agricultural produce would have added to the vulnerability of the overall system even in the normal scenario, through a built-in imbalance of supply and demand. External stresses, as mirrored in a dry scenario, are very likely to have aggravated this situation, threatening the food-security of the large sites and the overall power balance. Any societal transformations that followed, however, should rather be seen as symptoms of a pre-existing vulnerability than as direct effects of climate change.

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The data and R code that support the findings of this study are (a) given in the supplemental material as well as (b) openly available at DOI 10.5281/zenodo.3478243. Archaeological site data are available from the corresponding author upon reasonable request. Climate information are available upon request from 'Greek Special Secretariat for Water' (http://ypeka.gr/Default.aspx?tabid=430&locale=en-US&language=el-GR).

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