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Land use, climate change and 'boom-bust' sequences in agricultural landscapes: Interdisciplinary perspectives from the Peloponnese (Greece)

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ABSTRACT

We show that long-term and comparative studies are imperative if we are to identify the interlinkage between land use and climate and understand how vulnerabilities build over time and ultimately decide the societal outcomes of climate change. Using a long-term perspective, we study changes in both the extent and intensity of land use in NE Peloponnese, Greece, across more than two thousand years, from the end of the Middle Bronze Age to Roman times (~1800 BCE–330 CE). When set against a backdrop of paleoclimate information from the Peloponnese, the correspondence between changes in land use extent and climate is significant. Sequences of booms and busts in ancient societies have previously been connected to cycles of agricultural intensification and the balance between population and food supply. Our results suggest that climate can amplify such cycles, but also – importantly – that societies create their own futures in the way that they are able to balance agricultural strategies relative to climate and climate change. Climate conditions may facilitate additional expansion during boom periods, supported by socio-political control functions, but also introduce significant impediments to previously successful strategies and ultimately lead to a crisis through an overexploitation of existing resources.

1. Introduction

Climate acts as a significant determinant behind the performance of agricultural regimes. Its influence can be traced both in terms of short-term, high impact events and in terms of changes taking place within longer-term climatic trajectories. Importantly, climate conditions in a specific location not only motivate certain types of land use, but subsequent changes to precipitation and temperature may also render previously successful land use strategies unsustainable. This built-in sensitivity is especially apparent among agricultural societies, and in regions with low and/or variable rainfall. This sensitivity remains at least as relevant today as it was in the past, and it is increasingly stressed how knowledge of past land use can help formulate future land use polices (Ellis et al., 2013; Harrison et al., 2020) and to understand the variable persistence of societies relative to climate change (Armstrong et al., 2017; Kintigh et al., 2014). Recent studies of vulnerability within past societies have focused specifically on demographic changes and food supply in the face of climate change (Ingram, 2018; Nelson et al., 2016). The critical relationship between these two factors formed the core of the arguments presented by both Thomas Malthus and Esther Boserup (Boserup, 1965; Malthus, 1798), whose arguments are still commonly used by policy makers and land use scientists today (Ellis et al., 2013; Meyfroidt et al., 2018; Smith, 2014; Soby, 2017). In specific reference to the ancient Mediterranean, Karl Butzer has more recently highlighted the "cyclic alternation of agricultural intensification and disintensification" (Butzer, 2005, p. 1775), wherein long-term cycles of population growth, coupled with a greater investment of labour, were followed by decline. In Butzer's model, the development of strategies involving agricultural intensification (i.e. greater investment of labour) enabled the full utilisation of Mediterranean polyculture, i.e. the risk-reducing blend of grains, herd animals and orchards characteristic of the area still today.

Key to the theories of Malthus, Boserup and Butzer was the issue of agricultural intensification. In their models, however, agricultural intensification occurred alongside a more general societal intensification (i.e. an increased overall economic output), observable through intensified trade, connectivity, infrastructure, and the increased size and number of settlements, for example. Butzer, seemingly influenced by a Boserupian perspective, viewed agricultural intensification as enabling rural population growth and urban development, which in turn acted as a catalyst for increasing societal complexity – a societal 'boom period' that reflected "a systemic interlinkage between ecology, intensification,

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demography and politico-economic integration at the regional level" (Butzer, 2005, p. 1776). While Malthus' placed less emphasis on the diachronic view advocated by Boserup and Butzer, he was concerned with general societal well-being, achieved through a balanced relationship between population and food supply. In the current study, we will examine the interlinkage between ancient land use and climate change in NE Peloponnese, southern Greece (Fig. 1), in order to investigate how strategies, content and the spatial configuration of land use may have been affected by climate change, and how such changes may have affected the overall well-being of societies. In order to explore these changes, we contend that a long-term perspective is absolutely crucial (Dearing et al., 2010; Schoon et al., 2011) and provide a diachronic and comparative analysis spanning from the end of the Middle Bronze Age to the Middle Roman period (~1800 BCE–330 CE: Table 1) (Weiberg et al., 2016, 2019a). Importantly, our data provides evidence for climate change as a feature of societal expansion as well as contraction, thereby highlighting the need for studies of human-environment interaction that move beyond the common focus on crisis and 'collapse' (Diamond, 2005; Weiss, 2017). For ancient Greece, this discourse has been especially prevalent in relation to the societal transformations around 2200 BCE and 1200 BCE and their possible correlation with known rapid climate change events (e.g. Cline, 2014; Drake, 2012; Jung and Weninger, 2015; Kaniewski et al., 2015; Knapp and Manning, 2016; Middleton, 2017; Weiberg and Finné, 2018), with much less attention paid to the role of climate change in historical periods on the Greek mainland (Bonnier and Finné, 2020; Bresson, 2014; Camp, 1982; Post, 2017; Weiberg et al., 2016). Here, we provide a perspective that spans between and beyond notional 'collapse' periods, hoping to encourage further comparative studies in the future.

In this study, we make use of settlement data obtained from field

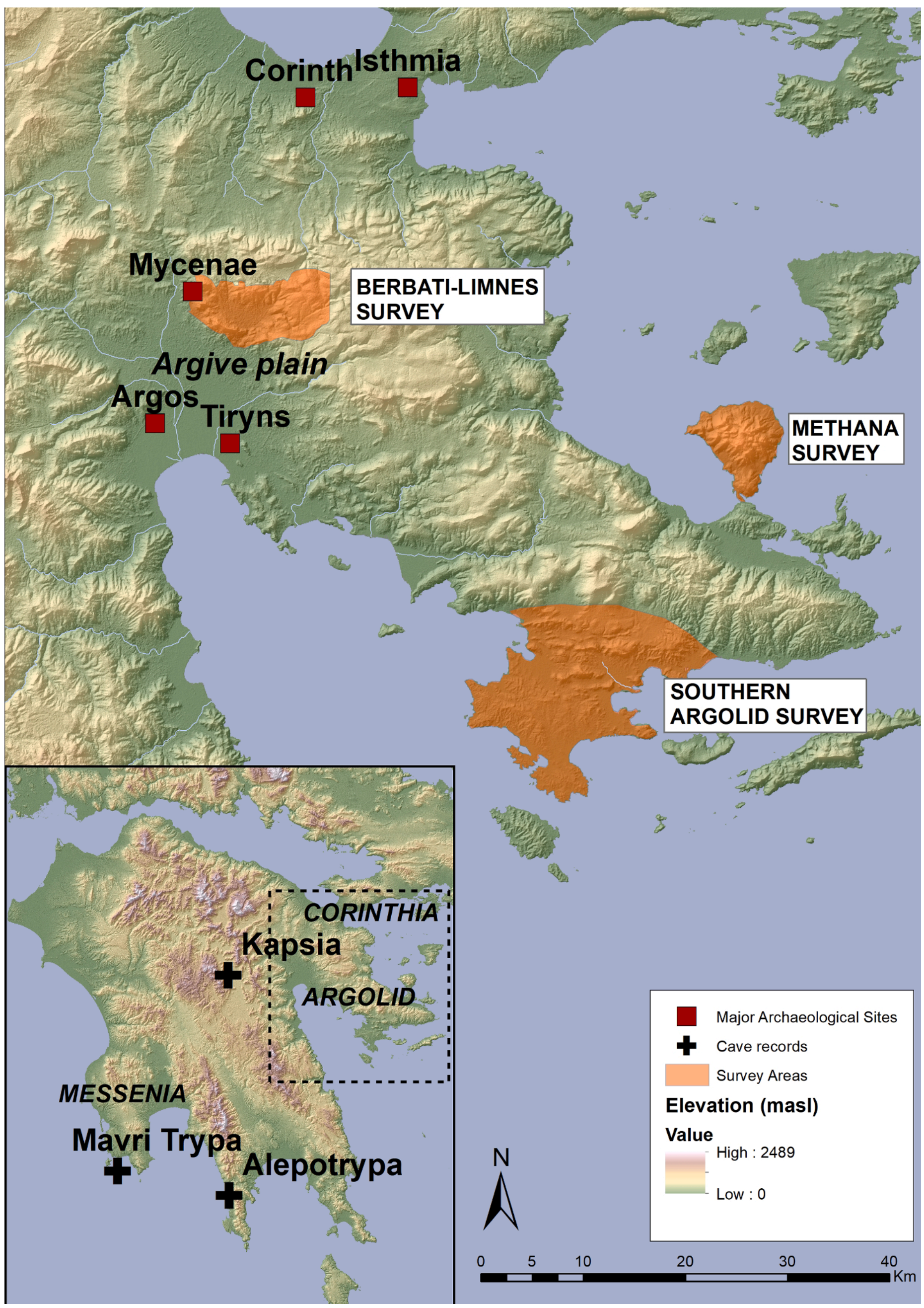

Fig. 1. Map of the study area including settlements mentioned in the text, as well as the outline of the survey areas and location of caves providing paleoclimate information utilised for the analysis.

Table 1
Relative chronology and the archaeological periods, with abbreviations, used in the present study, with absolute timeframes before present (BP) and in BCE/CE terminology (Cavanagh et al., 2016; Manning, 2010; Wild et al., 2010), as well as the duration in years of each archaeological period. Italicised periods are only outlined in relation to variations in the extent of possible land use (EPLU).

Relative chronology	BP (present 1950 CE)	BCE/CE	Duration in years
Early Helladic I (EH I)	*5200–4600*	*3250–2650*	*550*
Early Helladic II (EH II)	*4600–4150*	*2650–2200*	*450*
Early Helladic III (EH III)	*4150–4050*	*2200–2100*	*100*
Middle Helladic I–Middle Helladic II (MH I–II)	*4050–3750*	*2100–1800*	*300*
Middle Helladic III–Late Helladic I (MH III–LH I)	3750–3585	1800–1635	165
Late Helladic II (LH II)	3585–3370	1635–1420	215
Late Helladic IIIA (LH IIIA)	3370–3280	1420–1330	90
Late Helladic IIIB (LH IIIB)	3280–3150	1330–1200	130
Late Helladic IIIC (LH IIIC)	3150–3025	1200–1075	125
Protogeometric (PG)	3025–2850	1075–900	175
Early Geometric–Middle Geometric (EG–MG)	2850–2750	900–800	100
Late Geometric–Archaic (LG–A)	2750–2450	800–500	300
Classical–Early Hellenistic (CL–EHL)	2450–2096	500–150	350
Late Hellenistic–Middle Roman (LHL–MR)	2096–1620	150 BCE–330 CE	480

surveys to model the spatial distribution of land use and paleoclimate data derive from speleothems collected in Peloponnesian caves (Fig. 1). The survey data is complemented by general information from other archaeological sources regarding the details of land use and societal structures. Synthesised pollen records provide additional information about the ways in which patterns of land use impacted the surrounding landscape. Due to a rainfall gradient caused by a north-south trending mountain range and a primarily eastward transport of moisture, NE Peloponnese is one of the driest areas of Greece ("HNMS Climatic Atlas of Greece," n.d.; Nastos et al., 2013). The region is thus likely to be more sensitive to rainfall variability and therefore reveal clearer evidence for fluctuations in land use relative to climate change than other parts of the peninsula. A long-term study of this region therefore provides an excellent opportunity to study climate change effects on land use across millennia, and in this to facilitate further comparisons between periods. The results of this work have the potential to augment our understanding of vulnerability of agricultural societies to climate change in dryland environments (Kok et al., 2016; Roberts, 2011).

1.1. *Land use and climate*

In attempting to estimate the effects of climatic change on ancient societies, it is essential to first establish the nature of prevailing climate conditions in the study region, and to integrate this with knowledge of local subsistence strategies. The agricultural economies of ancient Greece, which were based largely on rainfed winter wheat and barley, relied heavily on rainfall to secure reasonable output from the fields. There was and still is a strong link between the amount of rainfall and crop yields (Aschonitis et al., 2013; Halstead, 1989; Tigkas and Tsakiris, 2015). The amount of rainfall varied between years, leading to fluctuations in the quality and quantity of harvests (Garnsey and Morris, 1989; Halstead, 2000; Roberts, 2011). Studies show that ancient farmers would have been well-equipped to deal with such variability by mobilising storage strategies and a mixed crop and animal repertoire that served to mitigate for potential risk (Halstead and O'Shea, 1989; Marston, 2011). During periods when reductions in rainfall came with short intervals, however, the success rate of such interventions was likely diminished (Roberts, 2011). Conversely, in long periods of wetter-than-average conditions, stores would be ample and societal expansion possible (Kennett and Marwan, 2015; Palmisano et al., 2021; Sinha et al., 2019). While both wetter and drier conditions could have ramifications for society as a whole, the effects of climate change would depend on the inherent productivity of the land and socio-economic structures (Palmisano et al., 2021). By studying land use and in particular the spatial configuration of land use from a long-term perspective, it is possible to visualise the extent to which changing climate conditions in particular periods may have impacted agricultural land use patterns as well as influenced wider processes of social development.

Land use – defined as "the purposes and activities through which people interact with land and terrestrial ecosystems" (Meyfroidt et al., 2018, p. 53) – is a multidimensional concept that incorporates aspects relating to both the extent and the intensity of human interaction with land (Meyfroidt et al., 2018). Although archaeology provides information on both these aspects, the conceptual separation is seldom acknowledged (Styring et al., 2017). Here we follow the definitions by Meyfroidt et al. (2018), in which changes in land use *intensity* refers to practices that manipulate land productivity, by altering input per land unit (e.g. greater investment of labour as argued by Butzer), output per unit area (e.g. as argued by Boserup), or ecosystem properties. The *extent* of land use is seen in patterns of the spatial expansion and contraction (land appropriation, including deforestation, and abandonment), commonly conceptualised as patterns of 'boom' and 'bust' in archaeology (Bintliff, 1997; Pettegrew, 2010). In the case of boom-bust sequences, the focus is on the overall extent of land use, and not on the size of individual plots (or the intensity of cultivation in these plots) such as recently explored by detailed archaeobotanical and isotopic analyses (Styring et al., 2017; Vaiglova et al., 2014). This focus on the overall extent of land use, relating to the overall societal intensification in the models of Boserup and Butzer rather than to the application of specific measures on the level of individual fields or settlements, is employed in the present study when considering both the extent and intensity of land use. Measures to manipulate the extent and intensity of land use may be combined in several ways to fine-tune the critical balance between population and food supply, and to mitigate or respond to potential destabilising factors that threaten this balance. This study will therefore explore factors of land use extent and land use intensity separately in order to clarify the difference between them but also to query the potential for variable effects of climate change on these two different types of measures.

2. Material and methods

2.1. *Archaeological survey records*

Information on ancient land use extent – that is patterns of spatial expansion and contraction – can primarily be drawn from archaeological field surveys. Fluctuations in the number, size and distribution of sites can provide information on settlement systems and land use strategies, which in turn are interpreted to reflect changes in population levels (Bintliff and Sbonias, 1999; Palmisano et al., 2021, 2017). Archaeological surface survey has been a key feature of archaeological work in the Peloponnese since the 1970s. Currently there are 18 published survey records from the whole of the Peloponnese (Weiberg et al., 2016), all covering large chronological time spans but with varying resolution of the interpreted results. For the current study, we have used site data from the Berbati-Limnes survey (Wells and Runnels, 1996), the Methana survey (Mee and Forbes, 1997) and the Southern Argolid survey (Jameson et al., 1994). For a study of land use, however, site numbers are less useful than estimation of the space potentially utilised by the people active at each identified location (Bonnier et al., 2019). The site data has therefore been digitised and analysed in ESRI ArcGIS 10.5 using kernel density estimation (KDE). The GIS-based KDE analysis transforms the point-pattern data provided by the survey records to heat maps outlining the distribution of 'sites' (i.e. point locations identified through clustering of archaeological surface remains, mainly ceramics) in the landscape. The heat maps are based on a 2.5 km radius from each identified site, following previous estimates of catchment zones for Greek agricultural settlements (Bintliff, 2012). Following the method presented in Bonnier et al. (2019), the heat maps use a three-tiered kernel division representing a maximum extent of possible land use – a medium extent and a minimum extent, the latter of which shows only the high density of land use. The point pattern data and the subsequent KDE-analysis has been structured through a number of time frames defined by archaeological periods, allowing us to observe changes in the spatial distribution pattern and density of recorded sites between the different periods (Table 1). This is an estimate based not solely on the location of different settlements and the properties of their individual territories (cf. Whitelaw, 2000) but rather on the point-pattern distribution of groups of sites noted in archaeological surveys. The result is an estimation, in hectares, of the spatial extent of possible land use (EPLU) in each period and region covered by the archaeological surveys based on a likely spatial limit for agricultural activities. As an equal number of sites can result in different hectare values (Bonnier et al., 2019), however, the EPLU is also a measure of the degree of site dispersal. A general expansion of land use means that different parts of the topographically variable NE Peloponnesian landscape became utilised. As a next step, using a high resolution 5 m DEM of NE Peloponnese, we have therefore matched the different density surfaces with the topographic makeup of land. For the present study, we focus specifically on the gradient of the land (i.e. slope) used during the different archaeological periods (for all calculated values, see **Table A.1**).

2.2. Climate and paleoclimate reconstructions

The southern Greek mainland has a Mediterranean climate with wet, mild winters and hot, dry summers, with temperatures modulated by elevation. There are large differences in the spatial distribution of precipitation across this area. Of specific relevance for the Peloponnese is the pronounced rainfall gradient, resulting in overall wetter conditions in the western parts and more arid conditions in the eastern parts ("HNMS Climatic Atlas of Greece," n.d.; Weiberg et al., 2019a). Stalagmites generally offer the most highly resolved and chronologically best-constrained paleoclimate information from the Peloponnese and are therefore used for the purposes of the present paper. Variations in stable oxygen isotopes ($\delta^{18}O$) are interpreted to reflect moisture variability (Bar-Matthews et al., 2003, 1997; Finné et al., 2017; Kern et al., 2019) and the records are chronologically constrained by uranium series dating (U-Th dating) presented on an absolute time scale (Richards and Dorale, 2003). Paleoclimate information in this paper derives from three different caves (Fig. 1): Mavri Trypa Cave, SW Peloponnese (Finné et al., 2017), Alepotrypa Cave, S Peloponnese (Boyd, 2015), and Kapsia Cave, Central Peloponnese (Finné et al., 2014). Two different speleothems from Alepotrypa Cave cover the period of interest in this paper, stalagmite A6 was used for the period MH III–LH I to LH IIIC and stalagmite A1 from PG to LHL–MR based on the strength of their respective chronologies (Fig. 2).

2.3. Managing comparability between survey records and paleoclimate datasets

Combining the archaeological and paleoclimatological datasets presents challenges in terms of chronological resolution (Caseldine and Turney, 2010). The duration of the archaeological periods within the relative chronology vary (Table 1), and it is impossible to conclude if all survey sites assigned to a certain period were actually contemporaneous, and hence if the full EPLU was in use simultaneously. Instead, each of

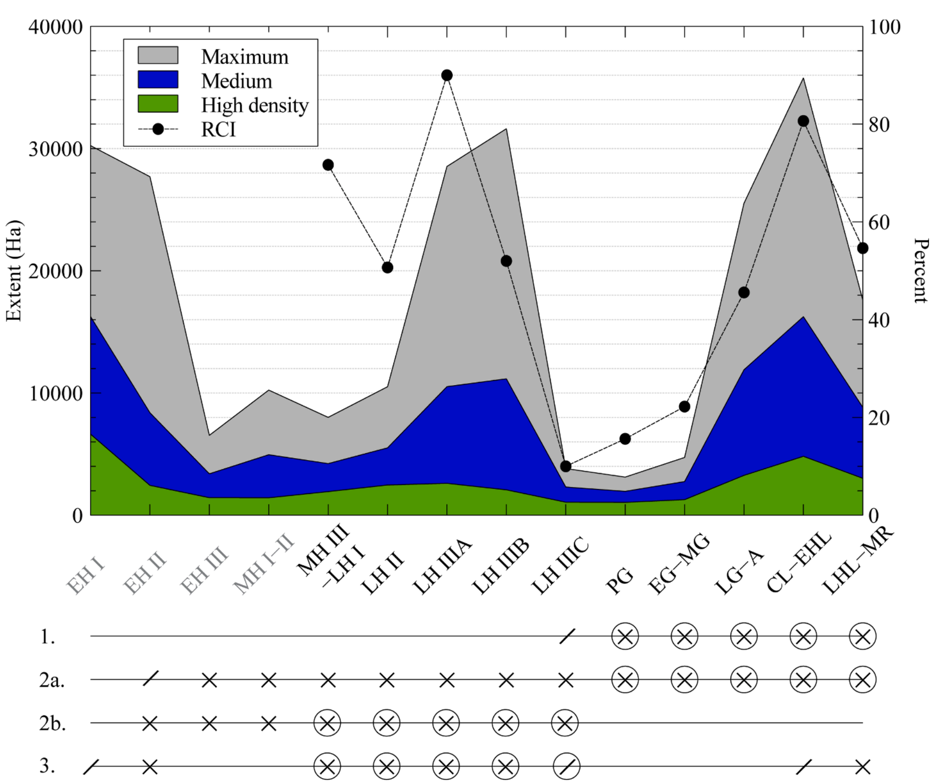

Fig. 2. EPLU (in hectares) for the EH I to the LHL–MR period (~3200 BCE–330 CE) with fluctuations in the maximum, medium and high-density extent depending on the site clustering in the landscape, and RCI for MH III–LH I to LHL–MR (~1800 BCE–330 CE). Note that RCI does not cover the period EH I to MH I–II due to the availability of climate data. The lower panel shows the archaeological periods that are fully (x) or partially (/) covered by the four speleothem records: Kapsia (1: Finné et al., 2014), Alepotrypa stalagmite A1 (2a: Boyd, 2015) and stalagmite A6 (2b: Boyd, 2015) and Mavri Trypa (4: Finné et al., 2017). RCI was calculated only for periods represented by at least two climate records, and only one speleothem record per location was used. Encircled x and / indicate individual RCI used to calculate the mean RCI for each archaeological period.

the periods recognised in archaeological surveys consists of an aggregate of data points that cannot be specified further in terms of chronology. Changes in site numbers, and in the EPLU, can be identified between periods but very seldom within a single specific period. Since the absolutely dated, often high-resolution climate records cannot adequately be reconciled with the relative chronology of the archaeological survey data, measures must be taken to downscale the resolution of the climate data. A Relative Climate Index (RCI) has therefore been constructed that re-scales and arranges our climate data to follow the archaeological periods, counting the number of data points in each record that fall above the mean value for the study period (cf. Ingram, 2018). The RCI was calculated by computing the proxy mean ($\delta^{18}O$) for each individual stalagmite for the period MH III–LH I to LHL–MR or for the longest-possible timeframe within this period. A RCI for each stalagmite and archaeological period was then calculated by finding the number of data points in each record that fall above the calculated mean value. A mean RCI for each archaeological period was calculated from the RCI of the individual caves. The Early Bronze Age is not included since the available climate records inadequately cover this very long archaeological period. By using the RCI we arrive at a resolution that is comparable to the chronological resolution of survey data and hence of the EPLU. This is a crucial measure to take, but it also means that we lose some of the higher-resolution information available for the climate situation that could enable a more fine-grained study into leads and lags in climate change and societal response. It should be emphasised, however, that archaeological uncertainties even at their lowest amount to at least a human generation (Finné and Weiberg, 2018; Manning, 2010), making specific chronological correlations highly tentative. In this study, therefore, we focus on lower resolution comparisons while emphasising the crucial role of slower working societal processes in determining the response mechanisms available within ancient societies in the face of climate change.

3. Results

3.1. The extent of ancient land use and climate

The calculated EPLU hectare values work as a proxy for the expansion and contraction, i.e. the extent of total land use, and results in three peak periods during which land use reached its greatest extent (Fig. 2). The first peak period is noted for the Early Bronze Age (the so-called Early Helladic/EH II period, ca. 2650–2200 BCE), the second during the Late Bronze Age (Late Helladic/LH IIIA and LH IIIB, ca. 1420–1200 BCE) and the third during the Classical to Early Hellenistic period (CL–EHL, ca. 500–150 BCE). These peaks correlate with periods of general societal expansion indicated by increasing site numbers, expanding contact networks and overall socio-economic complexity (Bintliff, 2012): the period of the so called corridor houses (EH II), the Mycenaean palatial period (LH IIIA and LH IIIB), and the core period of the *polis* system in the north-eastern Peloponnese (in CL–EHL). It should be noted that the areas surveyed by the projects utilised in the present study did not hold any key centres in any period, and as such they may be said to be peripheral to the more well-connected parts of the NE Peloponnese, such as the Argive Plain (with e.g. Mycenae, Tiryns and Argos) and eastern Corinthia (with e.g. Corinth and Isthmia). No surveys are available for these core regions, but the results provided by the surveys used here nevertheless correspond well with a broader, overall understanding of socio-economic fluctuations in different periods (Bintliff, 2012). If anything, the peripheral regions may preserve a better record of changing land use than the densely-populated areas that lay close to major centres.

The recorded changes in the spatial configuration of land use can now also be correlated with fluctuations in climate conditions during the same period. The calculation of a mean RCI results in three peak periods: MH III–LH I, LH IIIA and CL–EHL (Fig. 2), when the climate was relatively wetter. The chronological match between the RCI and the EPLU is significant (Spearman Rank Correlation Coefficient: $r = 0.745$, p 0.0133, $n = 10$), with the noted correspondence across time clearly indicating a meaningful link between the two. Only MH III–LH I diverts from the pattern (see below). Land use expansion is seen in wetter periods, while contraction occurs in periods characterised by drier conditions. Expansion of the EPLU in the boom phase means that larger parts of the landscape were utilised by people, thereby signalling a general expansion in land use. Especially relevant for the present study are any variations in the use of gradient land in the foothills and mountains of the NE Peloponnese. To illustrate the use of such land, the EPLU values were classified by slope, using three slope categories based on gradient and the suitability of the land for agricultural purposes, from low-gradient land (Slope 1: <10 degrees) to high-gradient land (Slope 3: >15 degrees). The results suggest that all slope categories are affected but that Slope Class 2 follow the trends of the RCI most closely (Fig. 3). Slope Class 2 corresponds to a slope of 10–15 degrees and incorporates land that may be cultivated without terraces but likely not without resulting in significant soil instability, leading to erosion (Bonnier et al., 2019; Whitelaw, 2000). In general, areas beyond the plains or valley floors are often composed of a thin soil cover, impacting the capability of the soil to store water and in turn reducing its overall fertility (Kosmas et al., 1993). Increasing use of such gradient land would thus have benefited from wetter conditions due to increased productivity, while drier conditions would have led to added stress on cultivation in these areas when compared to lower-lying areas that possessed thicker soil cover and better water-storage capacity (Kosmas et al., 1993). This would potentially lead to a realignment of land use patterns to areas with deeper soils (Bonnier and Finné, 2020).

3.2. The intensity of ancient land use and climate

It is apparent that periods of expansion and contraction in the EPLU relate to the overall scale of human activity in the landscape. This in turn correlates well with known developments and changes in socio-political institutions and likely in population structures (demography) (Bintliff, 2012). For our case study, it is also during the periods with the highest EPLU values that most measures relating to the intensity of land use, that is measures that manipulate overall land productivity (Meyfroidt et al., 2018), can be discerned. The primary visibility of such measures during boom periods can possibly be raised in support of a Boserupian view of agricultural intensification (Weiberg et al., 2019b) and reflects Butzer's cycles of intensification (Butzer, 2005). Information on the intensity of land use can be gleaned from archaeobotanical and zooarchaeological data regarding the time of introduction and the ubiquity of different animals and cultivars, as well as from archaeological data suggesting technical advancements and the development of new methods intended to boost land productivity.

The Late Bronze Age expansion period commences with the formation of the Mycenaean palaces in LH IIIA (around 1400 BCE) and a parallel increase in size of other central settlements. This development would have slowly led to increased population sizes at these locations, potentially to the brink of overpopulation. This could have resulted in food shortages in some regions or around major settlements, which then may have had to draw on resources from beyond their assumed territory as a means of covering their subsistence (Knitter et al., 2019; Wilkinson, 1994). Innovations with a potential to increase overall agricultural productivity that become visible in the archaeological material at this time include the introduction of new work animals such as mules, and new cultivars such as millet, spelt and free-threshing wheats (Weiberg et al., 2019b, with references). Mules and other work animals are capital-based inputs and technical advancements (cf. Meyfroidt et al., 2018) that facilitate transportation to and from fields and can be used in traction, allowing cultivation of a greater variety of fields, more effective cultivation strategies and potentially an overall greater agricultural output. Palatial administration of pairs of plough oxen recorded in Linear B texts also tell of an elite interest in agricultural efficiency and

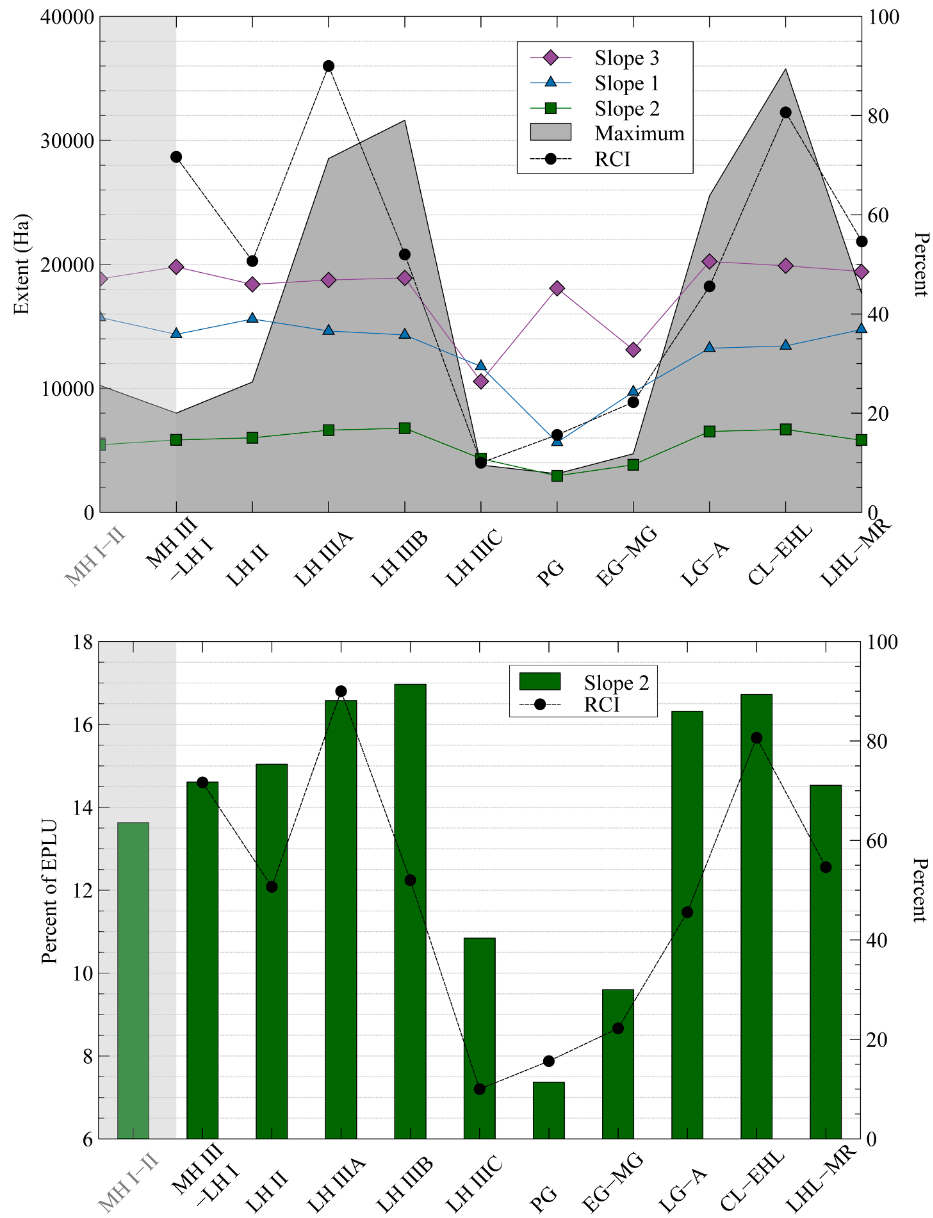

Fig. 3. Site location and climate: (upper panel) percent of all slope categories, against the backdrop of the EPLU maximum extent and RCI (cf. Fig. 2) and (lower panel) a detailed view of the specific percent of Slope 2 (maximum extent) relative to the RCI.

productivity (Halstead, 1999). A greater variety of cultivars allow a potentially better fit to different types of soils, environments, and economic functions. Free-threshing, naked wheats are also easier to process than glume wheats, enabling greater productivity, and may also respond better to increased rainfall (Riehl, 2009). This increased multifunctionality (Meyfroidt et al., 2018) of the agricultural economy is coupled with an expanding EPLU that is also suggestive of spatial diversification, i.e. an increase in identified sites spread throughout the wider landscape, indicating the utilisation of a greater variety of environmental and topographical zones allowing for a more versatile economy. Multifunctionality and spatial diversification could both work as risk management strategies (Halstead, 1989; Marston, 2011; Meyfroidt et al., 2018), but they also seem also to indicate efforts by populations to increase the overall productivity of the agricultural economy. Further evidence for the latter is provided by the large-scale use of agricultural terraces in some regions (Kvapil, 2012; Pullen, 2019). The construction of terraces comes with substantial investment of labour and terraces are in themselves enduring improvements in the productive capacity of land (Meyfroidt et al., 2018).

The incentives for expansion into new areas, may be found in a rising population (sensu Boserup) but they may also in part be gleaned from textual records that reveal a strong will among palace elites to document agricultural productivity and to control resources for the production of prestige goods. The palatially controlled produce was most likely destined for use within symbolically important gift-exchange networks (Bennet, 2013; Parkinson and Galaty, 2007; Pullen, 2019). A prime enabler for this development, however, may very well have been a reversal from relatively dry to wetter-than-average climate conditions in around 1440 BCE (Weiberg and Finné, 2018). Kennett and Marwan (2015) have recently acknowledged the positive effects of stable and favourable climate for periods of societal expansion, such as for example during the Mycenaean palatial period. Such conditions would not only have potentially increased local food security by boosting yields, but also created a positive feedback loop towards even higher levels of population growth.

In the prelude to the next boom period, the substantial expansion of rural sites and of EPLU from the Late Geometric to Archaic period (LG–A) onwards has been linked to demographic growth, which would have resulted in higher demands on agricultural production as well as the institutional significance of the *polis* in LG–A and CL–EHL. Measures to manipulate overall productivity of agricultural lands are similar to those in the LH IIIA and LH IIIB periods. Strategies to sustain food production, perhaps as a result of an increased production and demands on productivity, included an increased dominance of free-threshing (naked) wheat varieties, although barley remained an important cereal during these periods (Sallares, 1991). New plough types may have also facilitated the cultivation of heavier soils, though it is uncertain whether the use of these innovations had any direct effects on increasing the cultivation of cereals (Sallares, 1991, p. 348). Nevertheless, new plough types would indicate increased technological input and as such an increase in land use intensity (Meyfroidt et al. 2018). Whether or not agricultural terraces were commonly used in this period is still a matter of debate (Foxhall, 1996), but the distribution of small rural sites and the use of higher-gradient lands suggests that they were. During the LG–A and CL–EHL periods we also see a substantial increase in the cultivation of olives and grapes, which seem to have been cultivated to supply a trade in wine and oil – in some cases at the expense of cereal production (Izdebski et al., 2020). The expansion of such new cultivation strategies, both in terms of cereal cultivation and tree crops may have been stimulated by both wetter conditions and the growth of urban markets.

The increase in the number of small rural sites in CL–EHL, however, may also serve to indicate challenges for broader subsistence. Previous interpretations of survey data from Boeotia in central Greece have stressed increasing ecological challenges through agricultural overuse and soil exhaustion resulting from demographic pressures (Bintliff et al., 2007). In a Boeotian context, such agricultural stress has been suggested, based on off-site sherd scatters in the landscape, to reflect an increase in manure spread on agricultural fields in the hinterlands of urban centres. Manuring is a distinct measure to manipulate land use intensity, altering the output per unit area. An increase in manuring seems to have followed agricultural land use expansion and would have formed part of measures to maintain or increase the productivity of agriculture in the territory of specific *poleis*. Published survey data from the NE Peloponnese is not detailed enough to allow the identification of similar practices here, but a similar scenario is probable (Bonnier and Finné, 2020, but see also Forbes, 2013). That these developments generally occur under beneficial climate circumstances adds further layers to the narrative. Like in the LH IIIB case, such beneficial conditions may have pushed demographic growth and motivated changes in the agricultural strategies (both in terms of intensity and extent), possibly pushing agricultural land use to unsustainable levels. Notably, the best dated soil erosion record from NE Peloponnese show the highest sedimentation rates at the very end of the Late Bronze Age and in the Roman period (Fuchs, 2007), hence in the periods immediately following these two major expansion periods. This circumstance may thus support a causal link between land abandonment and soil instability, rather than soil instability at the time of high human pressure (cf. Andel et al., 1986). However, the cause-and-effect for soil erosion remain uncertain (Butzer, 2005), and factors of climate and the effect of pastoral activities, for example, should not be excluded.

3.3. Land use, climate and vegetation – A comparative view

Measures increasing both extent and intensity of land use can thus be identified for both LH IIIA and LH IIIB as well as for CL–EHL, increasing the multifunctionality of the agricultural economy. The content of both periods fit well with Butzer's definition of agricultural intensification, i.e. a greater investment of labour in order to increase overall agricultural productivity. The combined evidence relating to the extent and intensity of land use presents a picture of strong human impact on the NE Peloponnesian landscape during these periods. Such pressure is likely to be visible in vegetation cover, and in order to test this we turn to the pollen evidence using the recently synthesised pollen data from southern Greece (Weiberg et al., 2019a; Woodbridge et al., 2019). The question considered here is whether pollen evidence can further help us to understand the linkages between land use and climate.

Overall, the fluctuations of general anthropogenic indicators in the vegetation cover (here represented by the Anthropogenic Pollen Index: API) follow those of the EPLU and thus also the changes in the RCI (Figs. 2 and 4). API increases from MH III–LH I and reaches a maximum during LHIIIA and LH IIIB only to decline again until LH IIIC. From the low in LH IIIC, the API rises in the Protogeometric period (PG) and reaches its second highest level (of the shown sequence) in LG–A. There are two data points within LG–A, the second of which show a slight decline before a small increase to CL–EHL. The levels decrease drastically going into the Late Hellenistic to Middle Roman period (LHL–MR), albeit with a slight recovery already within that period. Notably, however, the API declines in LH IIIC is much less drastic than the one in

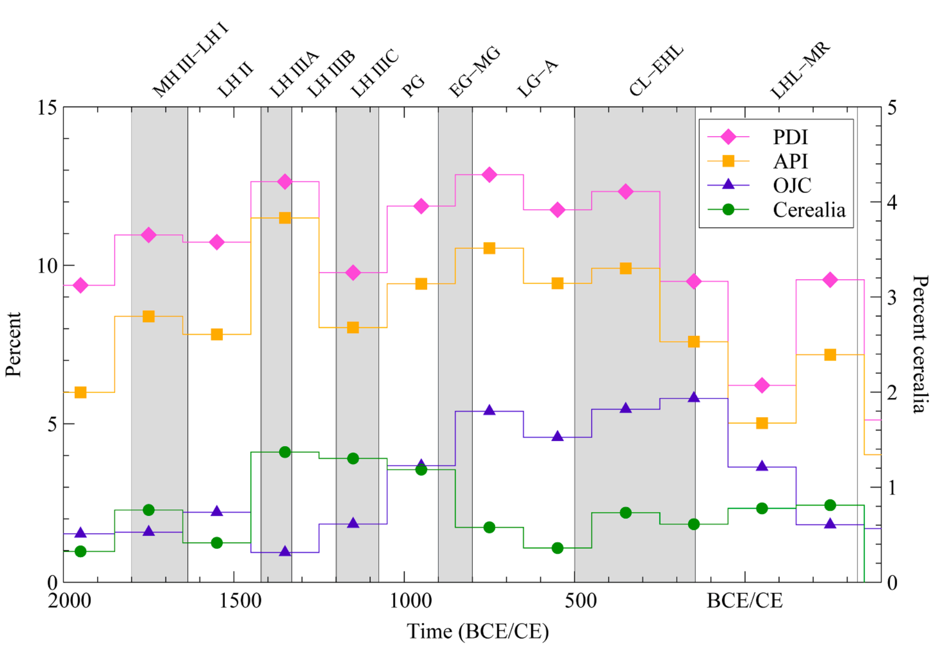

Fig. 4. Synthesised pollen data based on regional averages for defined 200-year time periods of a number of individual pollen records from southern Greece (Weiberg et al., 2019a; Woodbridge et al., 2019). Each point marks the chronological centre of the 200-year time period. The diagram include values (from the bottom and upwards) for Cerealia, cultivated tree pollen (OJC: *Olea, Juglans, Castanea*, which in southern Greece is primarily driven by *Olea*), a pastoral indicator (PDI: Pollen Disturbance Index) and an anthropogenic indicator (API: Anthropogenic Pollen Index). For details on taxa included in the indices and further references, see Weiberg et al., 2019a; Woodbridge et al., 2019). Note that Cerealia is displayed against a separate y-axis.

LHL–MR, while the opposite can be said for EPLU and RCI. This pollen data is based on a regional synthesis of twelve pollen sequences from southern Greece and thus not specific to NE Peloponnese, but the results still indicate that the LHL–MR changes in land use were more comprehensive than the ones in LH IIIC, based on API as a proxy. Beyond the API, the most pronounced peak in LH IIIA and LH IIIB is one of pastoral indicators (Pastoral Disturbance Index: PDI) (Fig. 4), followed by a drastic decrease in the same way as the API in LH IIIC (suggesting that pastoral indicators are a key component for change within the API: Weiberg et al., 2019a). Even if the PDI is high also from LG to LHL–MR, what stands out in the LG–A and CL–EHL periods is the high level of OJC (in southern Greece primarily driven by olive pollen: Weiberg et al., 2019a) that finds no parallel in LH IIIA and LH IIIB.

Connecting these variations in land use to climate, it should be noted that pastoral activities – especially herding of hardier animals such as sheep and goats able to forage in a greater variety of environments – are a useful component of risk management strategies (Marston 2011). Notably, zooarchaeological assemblages from the driest parts of southern Greece suggest an increase in goats – adapting better than sheep to drier landscapes – in the period PG to LG–A (Dibble and Finné, 2021). Beyond the balance between species, however, high PDI values appear more connected to periods of wetter-than-average climate conditions. Similarly, olives are drought tolerant, and it is noticeable that olive cultivation begin to increase during the periods with the lowest RCI (Weiberg et al., 2016), but it is equally noticeable that the most prominent increase come only at the same time as the RCI is increasing. Cereals, in contrast, would be expected to be affected negatively by lower rainfall (Aschonitis et al., 2013; Halstead, 1989). Despite this, the reductions in EPLU/RCI are not mirrored in any distinct reductions in cereal production such as we might expect during deteriorating climate conditions. Instead, the reduction in EPLU/RCI takes place in parallel with decreased levels of pastoral indicators (LH IIIC) and olive pollen (LHL–MR) (compare Figs. 2 and 4). Both of these distinct peaks, in PDI and OJC, are therefore likely to be primarily connected to special purpose production, and only indirectly to climate, if at all. The peak in pastoral activities in LH IIIA and LH IIIB may be indicative of the palatially-controlled textile industry, which also included control of large herds of sheep (known from textual evidence of the period: (Killen, 1993). The high levels of olive pollen in CL–EHL may suggest production destined for market sale, highlighting a partial alignment towards cash cropping strategies (also including grapes) that began during the LG–A period (Izdebski et al., 2020).

Apart from these obvious differences in content, there are also two ‘structural’ differences between the early and the late period. The first is that EPLU/RCI change appears slightly offset in LH IIIB, in that when RCI decreases there is continued increase in EPLU, while in LHL–MR the change is simultaneous (i.e. within the same archaeological period) (Fig. 2). These discrepancies may of course be due to chronological resolution but do also open up for a discussion of potential differences in the way societies responded to climate change, which brings us to the second difference that has to do with state control in periods of climate deterioration. In the early case, climate change coincides with a breakdown of state control, while the later period is linked with a strengthening of political interventions within an imperial framework.

It is impossible to know to which extent the high EPLU values during LH IIIA and LH IIIB were the result of increased population pressure or the needs of the palaces. More certain, however, is that when climate turned less beneficial, the agricultural economy appear to have been stretched and partly under significant control by the palaces (Finné et al., 2017; Weiberg and Finné, 2018). Beginning in LH IIIA, all evidence points to a strong human impact on the NE Peloponnesian landscape, which is enhanced in LH IIIB with massive building enterprises and landscaping projects that clearly indicate centralised control of resources and labour (Maran, 2009). Strong control and set patterns are not easily broken. The level of the investment of labour necessary to create and maintain terraces, for example, has been argued to hinder

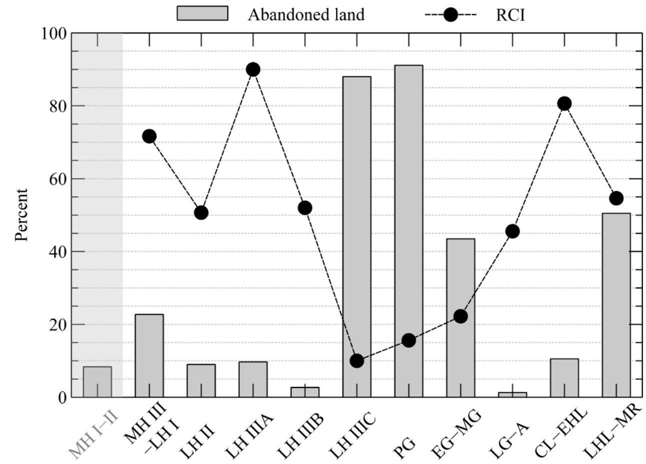

Fig. 5. Percent of abandoned land (based on EPLU in the preceding period) in relation to RCI.

land abandonment even when productivity decreases (Meyfroidt et al., 2018, p. 54). In this, continued expansion may very well have represented an accident waiting to happen (cf. Holling, 2001, p. 394; Maran, 2009). Coupled with drier conditions, LH IIIC saw a drastic decrease of EPLU and an abandonment of land that continued throughout PG to Early Geometric–Middle Geometric (EG–MG) (Fig. 5). The extent of these abandonments has no parallels in the history of ancient Greece.

The changes occurring in the next dry phase, during LHL–MR, are not as dramatic but can be observed in the spatial dynamics of land use and possibly in cultivation strategies. At this time there is a substantial reduction in the amount of olive pollen and of pastoral indicators in combination with a slight increase in the proportion of Cerealia (Fig. 4) (Izdebski et al., 2020; Weiberg et al., 2019a). The changes primarily signal shifts in local economic structures, and a shift in special purpose production, brought about by the incorporation of the Peloponnese into a new Roman imperial framework (Rizakis, 2014). In particular, the visible dynamics fit well with a political scenario of elite control of intensive cereal cultivation on the plains that took place at the expense of small-scale farmers in less productive parts of the landscape (as evidenced by the reduction in EPLU). As these changes correlate in time with an average reduction in rainfall, climate change may also have contributed. Although olive cultivation and herding are two activities generally well adapted to arid conditions, the use of hilly landscapes, often favoured for olive cultivation but also the probable location for many of the smaller family farms, would have been the first affected by reduced rainfall. It is also possible that the introduction of new Roman taxation systems, combined with a reduction in the general pattern of grain imports to Greece, would have prompted an increase in grain cultivation, though the evidence for taxation in the province of Achaea (the Peloponnese) is limited (Alcock, 1993). If these changes would have occurred at a time of reduced precipitation, wealthy landowners based on heavier clay soils with better water storage capacity would have been at an advantage (Bonnier and Finné, 2020).

4. Discussion

4.1. Land use, climate and the durability of agricultural economies

In our NE Peloponnesian case study, recorded changes in climate correlate well chronologically with general societal fluctuations across our 2000-year-long study period. When focusing on land use specifically, we find a close chronological positive correlation between shifting patterns of land use extent and climate. This suggests a meaningful link but not necessarily a linear relationship between the two. With proper contextualisation, EPLU is a useful tool for considering human behaviour relative to climate change. Measures to manipulate overall land use intensity, however, are more likely indications of the availability of resources in any one period, and of the means to control them. Land use intensity links to agricultural productivity but not necessarily to climate change. Similarly, the main changes in vegetation cover, identified in pollen data, may be linked to political and socio-economic change rather than climatic change. The chronological correlation between climate conditions and EPLU, however, strongly suggests that wetter conditions were party to the scale of land use expansion. The question that remains to be answered is how much of a part climate may have played in societal expansion overall.

Since rainfed agriculture was always at the very core of the economy, the direct effects of climate change on production may be regarded to be similar in the different periods considered here, but the means available to deal with productive variability would have been different. A primary difference was likely the levels of connectedness and integration (sensu Butzer) between different parts of society (Butzer, 2005), as well as between individual settlements or regions and the outside world. Connectedness, defined by Gunderson and Holling (2002, p. 50) as the "strength of internal connections that mediate the influences between inside processes and the outside world," or connectivity, defined by Biggs et al. (2012, p. 427) as "the way and degree to which resources, species, or social actors disperse, migrate, or interact across ecological and social landscapes," is a matter of the internal controllability of a society and related to the structure and strength of linkages within that societal system (Biggs et al., 2012; Holling, 2001). Both concepts are tied to resilience theory and are used, sometimes interchangeably, as factors that determine the capacity of a system to respond and change in the face of disturbances while still maintaining its identity (Folke et al., 2010).

The trajectories of change in the LH IIIA and LH IIIB were not the same as during the CL–EHL period. The beginnings of the expansion periods – in MH III–LH I as well as in LG–A – seem nevertheless to have been characterised by efforts to engage with the outside world (not only within the Aegean region but also beyond). This engagement was enhanced during the centuries leading to the peak periods (in terms of EPLU and socio-economic complexity) when the communities of our case study area took on a prominent role in these interactions. The emergence of these new engagements with the world beyond is often raised as a driver for the societal change. In MH III–LH I, influences from Minoan Crete are seen as crucial (Parkinson and Galaty, 2007; Voutsaki, 2016), and in the LG–A, colonies (*apoikiai*) were established in different parts of the Mediterranean basin and contributed to socio-political developments within the Greek mainland (Malkin, 2011). From these periods onwards, we see also an increasing homogenisation of the society as a whole, signalling closer bonds between different agents in the intra-regional contact networks, reminiscent of provinces uniting into large regional states as stipulated by Joyce Marcus' Dynamic Model (Marcus, 1998). The degree of political cohesion during LH IIIA and LH IIIB is still debated (Eder and Jung, 2015), but for the CL–EHL period we know that the *poleis* were largely autonomous political units even if smaller *poleis* could at times become subordinated to more dominant *poleis* and incorporated into broader political leagues (Hansen and Nielsen, 2004). In LH IIIA and LH IIIB as well as in CL–EHL, both material culture and written sources suggest a fluid interchange of ideas, trends and commodities across large distances. Human and natural resources were available and so was also the means to utilise and control them. The evidence suggest that it was the combination of these factors – resource availability and control – that made these societies both able and willing to build on the opportunities afforded by climate. An indication to this effect is the lack of land use expansion during the beneficial climate conditions in MH III–LH I. This wetter period was one of societal change and resource accumulation, with surplus turned into commodities for socio-political interaction, as visible locally in the increased expenditure on lavish graves and grave goods (Parkinson and Galaty, 2007; Voutsaki, 2016). Any general land use expansion beyond the main settlements came only later, however, after a slow process of centralisation and likely of population growth throughout MH III–LH I and LH II that culminated with the emergence of the Mycenaean palace system and palace economies in LH IIIA.

At the peak of the boom periods, EPLU was at its highest, and so too likely were population levels with their concomitant demands on an increasingly complex societal apparatus. This means that even if per capita spatial requirements did change only slightly across time, as recently suggested (Weiberg et al., 2019b), the totality of human pressure on the landscape had changed considerably from the earlier periods. The balance between population and food supply would be put to test. The theories of Malthus and Boserup both deal with this balance, or, in effect, the elasticity of food supply relative to population change (Smith, 2014; Soby, 2017). For Malthus, food supply was inelastic and therefore served to limit population growth to a certain level. Boserup saw elasticity in both factors, generated by the choice of agricultural methods, technological innovations, social and political factors (Boserup, 1965; Soby, 2017). This notion of elasticity is reminiscent of the idea of adaptability – "the capacity of actors in a system to influence resilience" (Folke et al., 2010, table 1) – prominent within resilience theory and also to the definition of the concept of resilience itself, insomuch as this represents a capacity to deal with change and continue to develop (Stockholm Resilience Centre, n.d.). Continued development at a time of stress is dependent on the flexibility within society and on the alternatives available (Smith, 2014). Connectedness and integration will boost societal flexibility and resourcefulness over the short-term. In the long-term, however, as land use and societal strategies become increasingly more dependent on certain links and resources, connectedness may lead to rigidity or inflexibility (Biggs et al., 2012; Schoon et al., 2011), and thereby make societies more vulnerable to any internal and external factors that threaten the state of affairs. Climate is an important external factor that introduces limits to human life in a way that population and food supply do not. Climate can therefore be argued to introduce inelasticity into normally elastic factors. As such, it could be a factor in generating a Malthusian crisis, disturbing the balance between population and food supply and ultimately leading to a contraction similar to that seen in the EPLU and in the society as a whole during LH IIIC.

In order for climate change to become a crisis, however, the affected society must fail to adapt. This may have been the case for the LH IIIB societies in NE Peloponnese, during which the scale of human activities seemingly continued to increase regardless of deteriorating climate conditions, thereby pushing resource use beyond the critical envelope. The contraction in land use during LHL–MR times, following the expansion during the preceding period, may in a similar way be understood as part of a broader pattern where previous land use had placed a strain on soil capabilities. Additional stress in the form of drier conditions could have made small-scale farmers producing crops for both subsistence and market sale (and in the LH IIIA and LH IIIB also as provisions for the palaces), in particular those living on less productive land, more vulnerable. Such vulnerability was in LHL–MR further enhanced by increasing imperial demands for wheat crops, which together with the suggested climate changes may have caused a mismatch between production modes and environmental constraints as has, for example, been argued previously for Roman Gordion in Asia Minor (Marston, 2015). Large-scale landowners with access to better soils, with better water storage capacity, would therefore have benefited and may have capitalised on this situation (Bonnier and Finné, 2020).

5. Conclusions

Our study provides evidence for the interlinkages between land use and climate across more than two millennia and across two boom-bust sequences. The RCI masks short-term climate change but enhances comparability with the lower resolution archaeological record. The result is a strong correspondence between EPLU and RCI suggesting that climate conditions worked to amplify land use expansion. Measures to increase the intensity of land use is not clearly connected to climate but rather to the scale of human activities and the resources available, enabling added force in boom periods. However, what made these societies able to expand in the way they did (making the most of the possibilities offered by climate and other factors) in the relative short-term, did also contribute to making them vulnerable from a long-term perspective. Climate change can introduce real impediments for continued intensification and the management of food security along Boserupian lines. Climate deterioration appears in particular to affect land use on more marginal soils and in locations beyond key regions and settlements that retain their relevance through time. Such land use changes are likely to impact food supply and overall resource availability, potentially leading to something reminiscent of a Malthusian crisis. When viewed from a long-term perspective, however, it is evident that societies, in many respects, create their own successes and crises, and the outcome of climate change is therefore dependent on prior socio-economic settings and, perhaps especially, socio-political control functions.

As changes in agricultural land use (extent and intensity) and climate both have the potential to increase productivity, a balance needs to be found between them to ensure durability within agricultural economies. Chronological correspondence between periods of climate change and socio-economic change (whether booms or busts) should therefore not immediately be translated into climate causation. Internal factors govern the outcome of external influences. Merely stating chronological coincidence is therefore not enough. We need to ask why then and why there, whether we are specifically interested in booms or busts, or the full boom-bust sequence. As the long-term perspective adopted for the present study has shown, we may take this argument even further and suggest that the study of merely one boom-bust sequence may not be enough. Comparative studies between different boom-bust sequences add value to context-specific analyses, and provide important information of more general relevance regarding the durability of agricultural economies.

CRediT authorship contribution statement

Erika Weiberg: Conceptualization, Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. **Anton Bonnier:** Conceptualization, Investigation, Formal analysis, Data curation, Visualization, Writing - review & editing. **Martin Finné:** Conceptualization, Investigation, Formal analysis, Data curation, Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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