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Examining Land-Use through GIS-Based Kernel Density Estimation: A Re-Evaluation of Legacy Data from the Berbati-Limnes Survey

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ABSTRACT

The use of archaeological survey data for evaluation of landscape dynamics has commonly been concerned with the distribution of settlements and changes in number of recorded sites over time. Here we present a new quantitative approach to survey-based legacy data, which allows further assessments of the spatial configuration of possible land-use areas. Utilizing data from an intensive archaeological survey in the Berbati-Limnes area, Greece, we demonstrate how GIS-based kernel density estimations (KDE) can be used to produce cluster-based density surfaces that may be linked to past land-use strategies. By relating density surfaces to elevation and slope, it is also possible to quantify shifts in the use of specific environments on a regional scale, allowing us to model and visualize land-use dynamics over time. In this respect, the approach provides more multifaceted information to be drawn from archaeological legacy data, providing an extended platform for research on human-environment interactions.

KEYWORDS

landscape archaeology; legacy data; archaeological GIS; kernel density estimation; archaeological survey; ancient land-use; Berbati-Limnes survey

Introduction

Digital approaches offer new ways through which archaeological legacy data may be approached and re-evaluated to examine past landscape dynamics. In the current study, we demonstrate how GIS-based kernel density estimation (KDE), can be used as a suitable method to quantitatively assess shifts in land-use patterns by using distributions of sites from previously published archaeological datasets. More specifically, we test how density surfaces produced through KDE can be intersected with topographic data provided by high resolution Digital Elevation Models (DEMs), and how these can be used to examine and visualize shifts in the use of specific environments over time.

Previous discussions on past landscape dynamics have often involved diachronic comparisons of site numbers, including more qualitative discussions of distribution patterns (for Greece, see for example Alcock [1993], Bintliff [1997], Stewart [2013], and Weiberg and colleagues [2016]). Such approaches have been useful in illustrating settlement fluctuations linked to socio-economic developments, but are at the same time limited in the type of quantitative information they convey (Whitelaw 2000; Witcher 2008). Through the method outlined here, we demonstrate how KDE can be used to quantitatively assess landscape dynamics, moving beyond diachronic comparison of site numbers. Given the simplicity of GIS-based KDE, as well as the subsequent intersecting applications demonstrated in the current study, it forms a suitable and easily applied method through which we can obtain new information that allows robust comparisons of land-use patterns between periods.

In the current study, our method of GIS-based KDE will be exemplified through analyses of data derived from the Berbati-Limnes Archaeological Survey (Wells and Runnels 1996), conducted by the Swedish Institute at Athens in the late 1980s and early 1990s in the Berbati valley, which is situated in the northern Argolid, in the Northeastern Peloponnese, Greece (FIGURE 1–2). We will argue that KDE can provide additional perspectives on patterns of land-use in the Berbati valley and the neighboring Limnes area from prehistory to the 4th century A.D., adding to the interpretations of site dynamics and distributions presented in the original publication of the survey results.

Mediterranean Survey, Legacy Data, and GIS

The method outlined in the current study has been specifically developed for evaluations of legacy data in the form of published site distributions recorded through archaeological field surveys. In Greece (as well as in other parts of the Mediterranean region), a wide range of data has been made available over the past decades through survey projects utilizing different methods and employing varying degrees of spatial coverage (for a geographic overview of Peloponnesian survey projects, see Figure 1). Intensive surveys engaged in the systematic recording of artifact scatters in plow zones provided a significant advancement in regional research agendas from the 1970s and onwards (for projects forming part of the new wave of intensive survey in Greece in the 1970s and 1980s, see Bintliff and Snodgrass [1985, 1988a], Wright and colleagues [1990], Cherry and colleagues [1991], Jameson and colleagues [1994], and Bintliff and colleagues [2007]).

Intensive investigation methods provided ways to examine the distribution and location of “sites” as well as “off-site archaeology” (i.e., scatters of surface artifacts between places defined as sites [Bintliff and Snodgrass 1988b; Alcock et al. 1994; Bintliff and Howard 1999; Bintliff 2000; Pettigrew 2001; Bintliff et al. 2002]). The published data have, however,
usually been concerned with the distribution of sites or localities carrying specific archaeological signatures (the semantic qualities attached to the word “site” itself have been much debated in the archaeological survey literature, see for example Gallant [1986], Wells [1996a: 16–18], and Jameson and colleagues [1994: 221]). More recent survey projects have also employed sophisticated spatial models for evaluating the distribution of both artifact scatters and sites.
At Antikythera in Southern Greece, for example, the results of intensive artifact level survey have been tested through spatial analyses, which demonstrate that archaeological locations (or sites) are not randomly distributed on the island but highlight the significance of access to resources such as spring water, flat land, and lighter soils (Bevan and Conolly 2013: 106–109). The spatial analysis employed at Antikythera further demonstrated how the patterning of archaeological artifacts in the landscape reflects multiple and complex aspects of habitation and land-use in different periods (Bevan and Conolly 2013: 112–157).

Legacy data derived from site-based surveys will not always provide such a high-resolution picture of artifact distributions as that available from Antikythera, but they can nevertheless be re-evaluated through spatial analyses that provide additional perspectives on land-use. More complex interpretations and quantitative evaluations of site distributions are highlighted by Whitelaw (2000), for example. In a paper focusing on survey data from the island of Keos, Whitelaw demonstrates how site data can be correlated with specific locations, incorporating different topographic parameters (Whitelaw 2000: 234–237). The Keos study highlights the importance of quantification for comparisons of dynamics between time periods in a specific regional setting. A substantial difference between Whitelaw’s method and our approach here is the use of GIS, providing possibilities for more exact quantification of spatial configurations and the use of hypothetical land-use surfaces for different periods. The quantifications produced through GIS-based KDE further allow for diachronic analysis of changes in land-use systems utilizing identical digital approaches for the chronologically structured datasets.

GIS-based research within Greek archaeology has been growing at a steady pace in recent years, including studies of legacy data and other approaches that move beyond field-based data recording as part of survey and excavations (Constantinidis 2001; Farinetti 2011; Donati 2016; Jazwa and Jazwa 2017; Argyriou et al. 2017). The use of GIS, of course, needs to be approached critically, since digital methods and mapping run the risk of masking uncertainties in the data and consequently in the archaeological interpretation (Sharon et al. 2004; Witcher 2008). It is therefore crucial to define the methods, assumptions, and theoretical frameworks informing such research.

In the current study, we follow a similar approach to that carried out by Argyriou and colleagues (2017) for different areas of Bronze Age Crete. However, while their study was specifically concerned with the relationship between sites and landforms, utilizing the topographic position index (TPI) of sites recovered through archaeological survey, we have focused on kernel density surfaces and examined how these can be used to understand shifts in land-use patterns through time. In part, this follows the recent calls by Gupta and Devillers (2017) for more time-sensitive visualization of archaeological data in GIS, although we do not primarily employ map-based visualizations of dynamics in the current study. Diachronic developments are instead illustrated through a series of graphs highlighting spatial dynamics.

**Kernel Density Estimation (KDE) and Land-Use Patterns**

The premise of KDE is to produce smoother visualization of break values for quantitative groups, building on the principle of a heat map distribution between core areas (kernels) and surrounding neighborhoods. KDE has increasingly been
used within archaeology to examine the spatial distribution and frequency of both archaeological sites and artifacts in different (global) contexts (Baxter et al. 1997; Wheatley and Gillings 2002: 186–187; Conolly and Lake 2006: 175–177; McMahon 2007; Herzog and Yépez 2013; Lindholm et al. 2013; Sayer and Wienhold 2013).

GIS-based KDE is carried out using a radius input (sometimes defined as bandwidth) through which the various density levels are calculated. The radius can be either manually or automatically defined. For the present study, we have used a manual 2.5 km input for all time frames, which is based on previous discussions of an idealized catchment zone of agricultural communities, representing an approximate one-hour walking distance for farmers commuting to their fields (Bintliff 2012: 271).

The first use of a defined catchment radius was presented by Vita-Finzi and Higgs, who argued for a catchment composed of 5 km for agriculturalists and a 10 km radius for hunter-gatherers in the Near East (Vita-Finzi et al. 1970). This type of catchment analysis was later reworked by Flannery (1976) for Mesoamerican villages, for which a radius of 2.5 km was proposed for mature agricultural landscapes. The 2.5 km radius has subsequently been used to represent a general idealized catchment for Greek agricultural settlements, particularly by Bintliff and others working with settlement archaeology and survey data in the central Greek region of Boiotia (Bintliff 1999, 2012: 271; Farinetti 2011: 42–43).

The 2.5 km radius should not, however, be understood as the defined catchment area of the individual sites included in the KDE. Specific catchment areas should be defined using more refined site-based cost-distance application within GIS, as is highlighted by recent research (Farinetti 2011; Becker et al. 2017). The radius instead provides a spatial framework specifically used for the purpose of GIS-based KDE, establishing an outer limit to the density estimation and using the input as a measure through which we can model and compare density patterns over time.

Density levels and “Extent of Possible Land-use” (EPLU)

Based on the KDE heat maps produced through the period specific site inputs, we have extracted hypothetical land-use surfaces, each defined as the “Extent of Possible Land-Use” (EPLU). The EPLUs represent a possible land-use surface based on the clustering of archaeological sites, measured according to the defined radius input, without any regard to the interpreted function or status of the sites. For the current study, two versions of ESRI ArcMap (10.3 and 10.5) have been used to perform all stages of the analysis. For the first step, we used the Kernel Density tool available in the Spatial Analyst tool box. The KDE rasters were then re-classified into a three-level distribution—consisting of a maximum extent, medium extent, and high-density areas—using natural breaks division (so-called Jenks), available in the ArcMap software, which divides data into groups inherent in the numerical data, based on the arrangement of values into groups following deviations from group means. The data are divided into uneven classes and separated according to significant changes (i.e., the natural breaks) in the data (Jenks and Caspall 1971). Within this three-tiered division, the “maximum extent” corresponds to the full area of the kernel, the “medium extent” forms the second tier of the kernel, and the “high-density area” corresponds to the identified hotspots within the heat maps. For further analysis and data extraction, each density surface was transformed into a polygon using the Raster to Polygon tool.

In the current study, no weighting was performed in the KDE, either by site size or by function, since our aim here was to examine how we can explore land-use dynamics based on site density and the presence of varying site clusters rather than densities of human populations. The heat maps produced through KDE should therefore not be understood as representing relative densities of people living in the landscape but rather the density of human activity (recoverable through the imprint of archaeological sites) available in the defined geographical context. With size-weighted distributions, the area of the maximum extent would remain unchanged (compared to the result of the current analysis), while areas of the medium extent and, in particular, high-density areas would be altered due to the increased weight of some of the points within the kernel. The unweighted heat maps nevertheless demonstrate that larger sites are generally located within the high-density areas, highlighting a non-random distribution of site clusters.

Case-Study: The Berbati-Limnes Survey

The Berbati-Limnes Archaeological Survey was carried out by the Swedish Institute at Athens between 1988–1990 (Wells et al. 1990; Wells and Runnels 1996), in the Berbati Valley and in the neighboring upland valley to the east, surrounding the modern village of Limnes, in the northern part of the Argolid (FIGURE 2). The survey was motivated by a wish to add a regional perspective to the results from earlier excavations at the site of the Mastos Hill initiated by Swedish archaeologists in the 1930s (Säflund 1965; Åkerström 1968, 1987). A further rationale behind the project was to document archaeological surface evidence threatened by rapid advances in mechanized agriculture (Wells 1996a).

The survey itself was performed on a field-by-field basis, where field walking was carried out at a 10 or 15 m interval between field walkers. The defined survey universe consisted of approximately 61 km², out of which approximately 25 km² were investigated intensively (Wells 1996a: 16). Very little off-site archaeology was recorded and the catalog of find spots for each period provides the primary evidence for human activity in the area in antiquity (Wells 1996a: 18). The original Berbati-Limnes survey was further complemented with an intensive artifact level investigation of the Mastos Hill in 1999, which added detailed information on the extent and chronology of habitation on this particular location (Lindblom and Wells 2011). The site of Mastos has therefore been included in the KDE analysis carried out in the current study, even though the Mastos Hill was not surveyed during the course of the fieldwork carried out in the late 1980s.

Findspots and chronological resolution

As a prerequisite for the GIS analyses, we have structured the digitized site distributions according to a number of defined time frames corresponding to the reported relative archaeological periods. The data collection and analysis in the current study have formed part of a broader initiative of synthesizing Peloponnesian site data dating from the Neolithic until the Middle Roman period and we have used the same chronological breaking points for the current study. We have
therefore performed KDE analyses for 19 "time frames" (i.e., period-defined distribution of sites used for the spatial analysis) that are based on the reported chronology for the findspots, and which span a period from the Early Neolithic until the Middle Roman (ca. 6800 B.C. – 300 A.D.) (FIGURE 3). Within this broad chronological focus, there are also periods where the lack of recorded archaeological remains suggests hiatuses in activity in the Berbati valley. The survey could not identify any secure findspots for the period between EH III and LH II periods (ca. 2200 – 1420 B.C.), even though material of LH IIB date was recorded at low quantities in some tracts (Schallin 1996: 169). The gap is filled by the later intensive survey on the Mastos Hill (not included in the original survey), during which abundant pottery dating to these periods was recorded (Lindblom and Wells 2011). These results suggest that Mastos was the only active site for this long period of time. A combined single point analysis was therefore performed for these periods, based on the Mastos Hill. The EPLU does correspond to the defined radius input and no real emphasis should therefore be placed on the results for this frame. In this sense, a cost-distance based catchment analysis of the Mastos Hill would be more informative, but the KDE/EPLU approach still produces data that allow their incorporation in the long-term model of land-use dynamics of the region.

In addition, very little secure evidence can be identified for the LH IIIC to Middle Geometric periods (ca. 1200 – 750 B.C.) in the Berbati valley, suggesting a hiatus at least of permanent habitation and land-use (Wells 1996b). These periods have therefore not been incorporated into the current analysis and are given null values in the quantification of the spatial extent derived from the KDE.

### Patterns of nucleation and dispersal

The heat maps produced as part of the KDE are exemplified in Figure 4, showing the results from the analysis of some selected time frames, which help to visualize patterns of dispersal and nucleation of land-use systems. The assessment of spatial shifts based on the heat-maps will, however, remain primarily qualitative in terms of the resulting analysis. A strength of GIS-based density estimation is that we can also extract spatial values from each EPLU (we have consistently used hectares as the preferred spatial measure), allowing us to track quantitatively the spatial changes occurring in the EPLUs over time, as is highlighted in Figure 5.

Previous assessments of nucleation and dispersal rates in other areas of the Greek mainland have largely been based on changes in the number of sites recorded in survey areas, in addition to more qualitative discussions on site distributions according to physical topography and environmental factors (Alcock 1993; Bintliff 1997). An increase in site numbers has usually been equated with a dispersed pattern of settlement and a reduction in site numbers has been associated with a more nucleated pattern (Jameson et al. 1994: 252–257).

By comparing the extent of density levels with the shifts in site numbers, we can state that the dynamics of the EPLUs over time are generally matched by the overall trend in site

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**Figure 3.** Time frames used for the GIS based KDE and chronological information. The time frame labeled LH II also represents the values for the Early Helladic III, Middle Helladic I and II and III, as well as Late Helladic I, since the only active site during this time occurs at the Mastos Hill. For the prehistoric periods (Neolithic to Late Bronze Age) we have used the absolute dates presented by Manning (2010), while for the historical periods (Late Geometric to Early and Middle Roman) we have primarily used the absolute dates provided by the final report of the Berbati-Limnes survey (Ekroth 1996; Penttinen 1996; Forsell 1996). EBA = Early Bronze Age, LBA = Late Bronze Age.
quantities, but we can also observe some interesting variability between periods. In time frames for which site numbers have been recorded in similar quantities, we can instead note variable trends of expansion and contraction, as well as nucleation and dispersal as highlighted by the KDE. Site quantities are, for example, relatively similar for the EA,
Figure 5. Quantification of the Berbati-Limnes EPLUs (in hectares) based on the KDE compared with the site quantities for each time frame. A) Long term variability in extent according to the full duration of all time frames. B) Dynamics in land-use extent between the Late Bronze Age and the Roman period.

Figure 6. Quantification of the Berbati-Limnes EPLUs (in hectares) based on the KDE according to absolute chronology.
LA, HL, and ER–MR time frames (between 9 and 11 sites per time frame), but the EPLUs, particularly in the medium and maximum extent, vary distinctively owing to the fluctuating distribution of sites in the valley and in the neighboring Limnes uplands (FIGURE 5).

A period in which we can observe a reduction in site numbers can still maintain a dispersed distribution of sites, as in the case of the HL time frame, while a period with a similar number of sites (for example the EA and LA time frames in terms of the Berbati Valley) can provide a much more nucleated distribution. In terms of the Late Bronze Age time frames, we can see that although the EPLU for LH IIIA2–LH IIIB1–LH III B2 decrease with the site numbers, the decrease in the EPLU is less dramatic. While the site numbers for LH IIIIB2 are less than half of those from the LH IIIA2 time frame, much of the EPLU is retained, highlighting that the dispersal of the remaining sites remained high.

The current method thus provides a more nuanced picture of the rate of dispersal and nucleation, as the resulting quantification is based on the spatial configuration of site distribution rather than the number of sites. It should be noted, however, that the values presented here are ordered according to periods defined by relative chronology and not in time slices of equal length (FIGURE 5). The division according to relative archaeological periods means that changes in land-use patterns may appear to be more rapid and dynamic when structured as part of relative archaeological periods. The long extent of the Neolithic and Early Bronze Age (between 6800 B.C. and 2200 B.C.), inflates the results compared with later periods (FIGURE 6), and in the case of the Neolithic to Early Bronze Age time frames, sites were probably not in continuous use. We have therefore focused our subsequent analysis to the period between 1450 B.C. and A.D. 300, which mostly consists of time frames of roughly similar length (FIGURES 3, 6).

**Intensification and extensification**

The rate of dispersal and nucleation was further explored via a land-use density index, which was determined by dividing the different density surfaces of the EPLUs by the number of sites within each time frame (FIGURE 7). Low values will consequently suggest more nucleated land-use, while a higher value is indicative of a more dispersed land-use. Overall, the broad trends in the Berbati-Limnes data suggests increasing land-use density in most of the historical time frames, owing to a generally more nucleated EPLUs compared to the Late Bronze Age frames (FIGURE 7).

Both the extent of EPLUs and the land-use density index can be used to suggest long-term dynamics in terms of spatial intensification and extensification, which have previously been discussed for agricultural dynamics in Mediterranean landscapes, particularly for prehistoric periods (Halstead 1999; van der Veen 2005; Currie et al. 2015; Bogaard 2017; Styring et al. 2017). In this context, spatial intensification may be understood as a higher degree of investment of labor (per hectare) into agricultural land-use, resulting in a smaller area that is more heavily worked. Extensification should instead be understood as a process of expansion into the landscape utilizing less labor-intensive agriculture, resulting in a lower input/output per hectare, but possibly providing a higher overall output (van der Veen 2005: 158).

These results from the KDE suggest a scenario favoring, or at the very least enabling, extensive agricultural strategies in the prehistoric time frames. Conversely, given the lower values on the density index for the historical time frames, this suggests a scenario that would usher in an increasing use of more labor-intensive agricultural strategies. The alternative is that during the historical period, people utilized land farther away from the settlement to a greater degree. The effect of the potentially lower preservation rate of prehistoric ceramic should not be overlooked and may have affected the quantity of sites recorded during the survey (Bintliiff et al. 2003; Davis 2004), but the KDE results provide both new and multifaceted data to expand such contextualization.

**EPLU and topography**

After the initial calculations of the EPLUs, the second step in the KDE method employed here is an analysis of how EPLUs are spatially distributed in relation to physical topography, using data extracted from a digital elevation model (DEM). The topographic data used for the current analysis has been derived from a 5 m resolution DEM, acquired from the Greek National Cadaster and Mapping Agency Ktimatologio.
All surfaces defined by the EPLU in the different time frames were vectorized as shapefiles (.shp), which were subsequently correlated with topographical data using the Intersect tool available in ArcMap. Although other types of data could easily be used for the intersect analysis, we will here focus on the correlation between EPLU surfaces and rasters with defined elevation and slope values (extracted as polygons for the intersect analysis).

**ELEVATION**

For the analysis of the distribution of EPLUs in relation to elevation, we created a raster with a defined 50 masl equidistant that could be intersected with the extracted density surfaces for the various time frames. The dynamics of the EPLUs regarding elevation point to a general trend of increased land-use at higher elevation in periods of substantial land-use expansion in the maximum and medium extent, as is visible for the LH IIIA2 (1390–1330 B.C.) to LH IIIB1 (1330–1250 B.C.) frames, and in the LCL–EHL (350–250 B.C.) frame (FIGURE 8).

As expected, the highest degree of variability can be found in the maximum extent of the EPLUs, while the high-density areas reveal a much more static picture in terms of elevation being used. This reflects a long-term focus of high-density site clusters within the Berbati Valley rather than the surveyed uplands to the east in the Limnes area. Moving away from the maximum extent, land at higher elevation is generally reduced in all time frames, but in the medium extent, the trend of expansion into land at higher elevation is still visible for periods with visible expansion of land-use areas.

It is important to stress here that land at high elevation is not the same as a high gradient landscape. High elevation areas may consist of flat ridges, plateaus, or upland valleys situated at a higher elevation. The comparison between EPLUs and elevation therefore provides little direct information on the use of marginal areas with thinner soil cover. A separate analysis has therefore been performed to correlate the EPLUs with the degree of slopes within them.

**SLOPE VALUES**

For the investigation of correlation between EPLUs and slope, we created a slope raster based on the DEM data, which was subsequently reclassified. For a first analysis we employed the definitions previously employed by Farinetti (2011: 17) for landform classifications in Boiotia, Central Greece. This classification system is constructed around five different slope categories ranging from flat or nearly flat ground to very steep slopes (FIGURE 9). For a second analysis, we utilized the slope classification provided by Whitelaw (2000: 234), in which the division of categories has been based on the impact of slopes on plowing and the potential use of terracing (FIGURE 10). The classification used by Whitelaw makes a clear distinction between land that can be suitably plowed without terracing (Slope class 1), land that may have been cultivated without terracing with an inherent risk of soil erosion (Slope class 2), and land requiring terracing for cultivation (Slope class 3). The slope classification presented by Whitelaw, while less detailed than the one based on Farinetti’s (2011) landform classification, is more directly connected to agricultural strategies and land-use.

To a certain extent, the high-gradient land in the EPLUs will simply reflect the physical topography of the area. The Berbati Valley is bounded by steep slopes formed by the
Psili Rachi range to the north and the Euboia (Prophitis Elias) and Rachi Kalogirou peaks to the south. Steep slopes are also significantly present in the uplands surrounding Limnes. An effect of this topographic situation is that the proportion of high-gradient land in the maximum extent is still high in periods with a more nucleated distribution (FIGURES 9, 10). However, this pattern is not maintained at all density levels. In the medium extent and high-density areas, the amount of steep land is significantly reduced in the more nucleated frames, demonstrating that high-gradient areas primarily form part of the outer edges of EPLU in the maximum extent. In the context of the Berbati-Limnes data, therefore, the medium extent provides the most accurate picture of dynamics since it reduces the amount of marginal land at the edges of the EPLUs. In the high-density areas, low-gradient land always forms the greatest part of the EPLU, but an increase in the amount of steeper ground is still visible for the dispersed distributions, for example in the LCL–EHL time frame. For purposes of comparison between time frames, the medium extent and high-density areas provide the most meaningful observations.

Previous discussions of site distribution have often been focused on the location of individual sites and their geographical positions according to factors such as slope, elevation, soil types, and geology (Jameson et al. 1994: 257–258; Mee and Forbes 1997; Stewart 2013). By using estimated density surfaces in the form of the EPLUs for this type of analysis, we are not merely evaluating the topographical circumstances of individual site locations, but also those of site clusters to extrapolate the proportion of topographic classes within the EPLU. The topographically-defined EPLUs thus provide data through which we can observe more large-scale changes in the use of more marginal soils situated on sloping ground. It is important to stress that the presence of land within an EPLU will not always signify actual usage. However, the available land is a measure of the types of land that could be used and in the medium extent and high-density areas more likely were used. In extension, the type of land-use and the total pressure of land-use has bearing on the resources needed to use/farm that land and vulnerabilities such usages may have inferred on societies.

The topographically defined EPLUs allow us to re-evaluate and expand upon the conclusion reached in final report of the Berbati-Limnes survey. One example can be seen in terms of the distribution pattern of sites dating to the Late Bronze Age. Many of the recorded LH IIIA2–LH IIIB1 findspots were located on slopes (FS43, FS44, FS12), including findspots situated at a low elevation (FS428) but in a high-gradient environment (Schallin 1996). The favoring of sloping and/or elevated terrain (e.g., mounds or knolls) for settlements
brings to the fore the sometimes reappearing interpretation that sloping ground was sought to keep the plains available for cultivation (see, for example, Forsén [1996: 117], who argues for the presence of this type of settlement strategy in the Berbati Valley during the Early Helladic period). Although the location of a settlement certainly can have economic motivations, as well as both functional (defense, control) and cognitive ones (Weiberg 2011), the suggestion that the choice of settlement location was driven by a wish to maximize farmland seems to be negated by the correlation of Roman period sites with flat land. Investment in agriculture including cash-cropping seems to have occurred in different parts of the Greek mainland during the Roman period (Rizakis 2013), and we can therefore assume that the Berbati Valley would have been part of similar land-use systems. If site locations were primarily determined by a wish to maximize available farmland, we would expect to find the estate situated on sloping ground at the edge of the plain.

The KDE approach further demonstrates that site location alone will only provide one piece of the puzzle. The potential increases in use of high-gradient land in expansive time frames suggest an increasing use of more marginal soils, in a pattern that goes beyond the locations of the sites themselves. Furthermore, the greater inclusion of high-gradient land also in the medium extent EPLUs increases the likelihood that sloping ground was used for farming. The higher proportion of sloping ground in the medium extent also increases the likelihood that agricultural terracing was in use in the Berbati-Limnes area during the latter part of the Bronze Age and in the Late Classical and Hellenistic periods. Early Modern and more recent terrace structures form a recognizable part of the slopes surrounding the valley and in the uplands bordering on the Limnes Plateau (Wells 1996a), but firm evidence for ancient agricultural terracing is largely absent and widespread use of terracing in ancient Greek agriculture has been questioned within previous research (Foxhall 1996, 2007). The reinterpretation of the Berbati-Limnes data presented here nevertheless gives some weight to the use of terracing, since the expansion of land-use into high-gradient land during boom periods in the Berbati-Limnes area would otherwise have been difficult to maintain (Whitelaw 2000: 234). The results of the KDE thus suggest that that terraces would have been needed in the Berbati-Limnes region in certain periods, such as LH IIIA2 and LH IIIB1, as recent studies have proven them to be in the relatively nearby area of Kalamianos to the northeast (Kvapil 2012).

Conclusion
GIS-based KDE provides a useful tool for the quantification of possible land-use dynamics and can facilitate a more

Figure 10. Slope variation in the Berbati-Limnes data using Whitelaw’s (2000: 234) tripartite slope classification. A, C, and E) Line graph of hectare values projected according to an absolute time scale based on the duration of the time frames in the maximum extent (A), medium extent (C), and high-density areas (E). B, D, and F) Proportion (%) of the different slope values in each time frame (defined according to the relative archaeological period) in the maximum extent (B), medium extent (D), and high-density areas (F). The proportion of each slope category is established using the hectare value of the specific slope class in relation to the extent of each EPLU for the different density levels. The proportions given in B are therefore dependent on the values provided in A, the proportions given in D are dependent on the values provided in C, and the proportions given in F are dependent on the values provided in E.
 nuanced and multifaceted discussion of boom-and-bust patterns occurring over time. The KDE approach allows us to visualize changes in the spatial extent and shifts in the topographic context of possible land-use over time, both through the GIS-generated heat maps but also through graphs plotting quantitative changes in the spatial extent of possible land-use. The method employed here has been developed with an explicit comparative intent. In the present study, comparisons are performed on a temporal scale, indicating differences between the prehistorical and historical periods. Through KDE, we can thus start to extract patterns of variability in land-use configurations between periods, which will provide new input to discussions on changing agricultural strategies and settlement dynamics. For example, this approach provides new quantitative data to complement earlier assessments of nucleation and dispersal patterns.

The analysis of the EPLUs in relation to topography further demonstrates how new and complementary types of land-use data can be extracted through the GIS-based KDE. By incorporating the slope and elevation data derived from the high-resolution DEMs, we can track and quantify changes in the topographical context of land-use in different periods. In general, the integration of slope values into the different levels of the EPLU provides the most interesting aspect of the potential shifts in land-use patterns, since we get a picture of dynamics relating to the use of sloping ground and consequently the use of more marginal soils and terraces in different periods.

In a second stage, this perspective should be extended by comparisons on a geographical scale, between different regions and survey datasets that have been produced through different intensive and extensive field methodologies. By utilizing density surfaces (here represented as the EPLUs) related to the clustering of archaeological sites (not only sites defined as settlements) we have sought to minimize some of the problems associated with comparing site quantities and integrating digitized legacy data. Ideally, we would further like to compare results of the KDE utilizing site inputs with off-site distributions recorded through intensive field walking. In the case of the Berbati-Limnes data, such information is not available in the final report limiting possible comparison with the result of the KDE.

Other intensive surveys in Greece where the distribution of off-site scatters has been more thoroughly published suggest that there is usually a defined presence of material surrounding both settlements and smaller rural sites, usually in the form of halos that tend to drop off at varying distances away from the recorded sites (Bintliff et al. 2007: 23–26). However, these distributions do not always provide the full geographical range of land-use associated with recorded sites, but may rather reflect the presence of more intensive land-use areas such as infields and gardens (Bintliff et al. 2007: 23–26; Winther-Jacobsen 2010: 271–272; Forbes 2013) for the complexities of interpreting off-site distributions as part of ancient agricultural processes. KDE analyses of recorded site distributions therefore offer complementary perspectives of possible land-use patterns and allow for possible evaluation of EPLUs in regards to the picture presented by off-site scatters.

In summary, the density surfaces and the type of quantitative data produced through the GIS-based KDE provide information related not merely to habitation patterns but also to aspects of land-use dynamics and ultimately the potential human pressure on the landscape in different periods. Such quantifications have considerable bearing on our understanding of the resilience of communities within these regions. Recent research has demonstrated the importance of incorporating high-resolution paleoenvironmental records into comparative efforts involving survey data to facilitate a better understanding of how changes in climate and environment may have impacted societies, and vice versa (Weiberg et al. 2016). Such integrated approaches demand quantification of possible land-use dynamics, going beyond changes in site and settlement numbers. GIS-based density tools such as KDE offer ways in which such new quantitative data can be created also on the basis of legacy data. The present study shows how GIS-based analysis of the spatial configuration of possible land-use can provide the basis for more multifaceted quantifications and open new ways to explore the linkages between environmental conditions, agricultural strategies and socio-economic transformations.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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