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# Household Sorting in an Ancient Setting*

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**Abstract**

We use archaeological data from ancient settlements of three different historical eras on a Greek island to construct novel measures of consumption. Using these, we show that luxury good consumption was higher closer to the center of nucleated settlements but shows no such pattern in a placebo settlement. We build a monocentric agglomeration model with heterogeneous households, luxury goods and endogenous labor choices that is consistent with the rich living closer to the center and consuming more luxuries. This result holds when intra-settlement transportation costs within the model are predominately time costs, as they mostly were in ancient history.

**Keywords**: Sorting, Luxury goods, Archaeology, Urban

**JEL Classification**: N93, R21.

*Socrates to Critobulus: I had been struck with amazement, I remember, to observe on some occasions that where a set of people are engaged in identical operations, half of them are in absolute indigence and the other half roll in wealth. I bethought me, the history of the matter was worth investigation.... What if I begin by showing you two sorts of people, the one expending large sums on money in building useless houses, the other at far less cost erecting dwellings replete with all they need; will you admit that I have laid my finger here on one of the essentials of economy?.... And suppose in connection with the same, I next point out to you two other sets of persons: The first possessors of furniture of various kinds, which they cannot, however, lay their hands on when the need arises.... The others are perhaps less amply, or at any rate not more amply supplied, but they have everything ready at the instant for immediate use.*

Xenophon

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# 1 Introduction

What causes different households to choose to live in different parts of an agglomeration is one of the key questions in urban economics. We use archaeological data from within four ancient settlements across three different historical eras on the Greek Mediterranean island of Antikythera to estimate how households sorted in early "urban" settlements. The data include precise spatial locations for finds of several different qualities of pottery, an important ancient consumption good.

Exploiting the fine spatial resolution at which the data are collected, we estimate consumption gradients for various pottery qualities. We find that higher quality goods are relatively more concentrated near the settlement centers for settlements with a known historical center with likely commercial activity, so called "nucleated" settlements. These settlements are agglomerated in some respect, with some centralized area used for commerce and social life. In contrast, we find little-to-no such relative concentration for a non-nucleated settlement that was a collection of farms and pasture land. We then extend the canonical Alonso-Muth-Mills (AMM) model by including a variety of non-durable goods of various qualities in a tractable way, and provide conditions under which household location sorting in the model can be inferred from our data on non-durable consumption.

At least since the latter half of the 20th century, lower income households have tended to be relatively more concentrated closer to the city centers in most cities in the United States while their richer counterparts were relatively more prevalent in the suburbs (see Glaeser et al. (2008) and many of the references cited below). More globally, this pattern does not always hold (Brueckner et al., 1999). The AMM model (Fujita, 1989) with heterogeneous households elegantly captures how different households differentially trade off commuting costs with the cost of land and thus sort themselves relative to a commercial center. As Glaeser et al. (2008) notes, the basic AMM model, with a plausibly low income elasticity of land demand, implies that the rich would outbid the poor in the center; worrying for the model given the sorting patterns that prevailed in the U.S. data. Understanding how the AMM model needs to be augmented to better reflect sorting in modern cities has therefore been a central focus for urban economics. Various avenues have been proposed, including modern transportation modes, public housing and public amenity provisions.[1]

Inferring the ways various amenities and technologies shape household location decisions, even within variations of the static monocentric city model, poses its own series of challenges however, and sorting conditions are much more difficult to obtain (see Duranton and Puga (2015); Fretz et al. (2017) for further discussion of these issues). Moreover, if inferences are based on modern cities, the preexisting, "sticky" built and settled environ-

[1]The list of references is vast but in addition to those cited already, see e.g. Mieszkowski and Mills (1993) for a survey.

ment can further complicate matters. Today's households make their choices conditional on the existing transportation network and character of the housing stock in various locations, which themselves are partially or wholly a product of the technologies and preferences of the past. Indeed, the possibility for differing equilibria based on legacy conditions are a feature of studies like Brueckner et al. (1999); Brueckner and Rosenthal (2009); Lee and Lin (2017).

In this paper, instead of extending the basic model to bring it to modern data, we, like LeRoy and Sonstelie (1983), study economies with little meaningful prior history to test the basic tenets of the AMM model in ancient settings without any known legacy infrastructure. To do this, we extend AMM by including a variety of non-durable goods of various qualities in a tractable way, and provide conditions under which household location sorting in the model can be inferred from our data on non-durable consumption. In the model, high quality or "luxury" merely implies that the elasticity of a luxury good's consumption share of total goods spending by a household is increasing in total goods spending.[2]

Obtaining testable hypotheses on sorting from millennia-old archaeological data is non-trivial. Our main challenge is that we do not have data on housing or land consumption; we only have data on various forms of "non-durable" consumption (ironic nomenclature given that the data for these goods were collected several millennia later after being consumed). Fortunately the data we use, collected by the Antikythera Survey Project (ASP),[3] feature several advantages. For one, the island the data was collected from has been sparsely inhabited in modern times. There has been relatively little data contamination over the centuries and the archaeologists were able to survey the entire island at a very fine level without worrying about disturbing (or being disturbed by) modern structures.

For another, the island was characterized by a phenomenon of "rollercoaster demographics" (Bevan et al., 2006). This features a rather unique pattern of settlements followed by long periods of near abandonment, implying a degree of temporal independence across eras. Moreover, we see a variety of types of settlements in the data. This means that we have multiple settlements, including a plausible placebo, to test our model. Finally, though our non-placebo settlements had some kind of commercial centers, there is no evidence that our consumption goods, which are pottery, were being mass produced in any quantity on the island. Thus the pottery finds in the data can be inferred to be from various kinds of consumption uses, rather than from remnants of production.[4]

Our nonparametric estimates offer fairly clear pictures that the concentrations of consumption were highest closest to the nucleated settlements' centers as well as providing

[2] As we describe below, though there are goods of differing quality in our data, they probably contain few goods that would be considered especially luxurious even by the standards of the time.

[3] https://www.ucl.ac.uk/asp, co-directed by Andrew Bevan (University College London), James Conolly (Trent University) and Aris Tsaravopoulos (Greek Archaeological Service).

[4] Examining production sites is very common in the archaeological literature, see e.g. Brown and Sheldon (1974); Gibson and Lucas (2002).

evidence of spatial gradients in quality. Our estimated gradients are consistent with theoretically predicted sorting in two out of the three historical eras that we study, namely the Hellenistic (ca. 325 BC-0 AD) and Late Roman (ca. 350 AD-650 AD) eras. In these we find evidence of luxury (higher grade pottery) consumption declining more steeply with distance from the center of settlements than lower grade pottery. The most ancient era that we study, the Minoan era (ca. 2700 BC-1200 BC), acts a type of placebo or contrapositive test. Bevan and Conolly (2013), p. 124, notes that Antikythera during this period was scattered with single family homesteads which did not coalesce into anything approximating a quasi-urban settlement.[5] Correspondingly, the gradients in luxury consumption for this era look markedly different.

Our work complements several strands of literature. It adds to the growing use of archaeological data or insights to test economic theory dating back at least to Hodder (1974a,b); Smith (1975). The works by Hodder compare the spatial distribution of fine versus coarse pottery wares (among other goods) near their respective production sites in Roman Britain to estimate how gravity-like models of "marketing" vary with product value. Intriguingly, Hodder (1974b) notes that fine wares have far greater relative concentrations within towns as compared to their outskirts. Rihll and Wilson (1987) looks at similar models for Ancient Greek settlements. Hodder and Millett (1980) estimate how the densities of Roman British villas vary with distance from a town center and attempt to correlate the hazard rates with various characteristics of the town, though sample sizes are very small. Fulford (1987) examines the percentage of imported pottery in total finds across Roman Britain to infer trade patterns.

More recently, Bakker et al. (2020) examines data on the location of ports from a similar period to ours to document trade and development patterns across settlements while Barjamovic et al. (2019) uses commercial records from Assyrian traders to estimate trade patterns and the location of lost cities. Izdebski et al. (2020) analyzes pollen data to infer production and trade patterns in Ancient Greece. Veal (2012) studies the distribution of different types of charcoal to try and infer demand for fuel in Pompei circa A.D. 79 and explores whether the distribution of charcoal correlates with known settlement patterns. Palmisano et al. (2017) contains a useful discussion of the use of raw counts of archaeological data (include pottery) to estimate demographic statistics and finds that these estimates compare well with other techniques.

Most inferences in archaeology and most economic hypotheses tested with archaeological data use relatively small data sets, and many of the references cited above are no exception.

[5] In fact, they state (p. 126) that "*there does not appear to be any strong preference for coastal connection to the outside world, or indeed any sign of an obvious port community, and there is also little sign of any settlement nucleation. What we are left with is an impression of individual small household farms whose closest major town centres are likely to have been off-island at Kastri on Kythera and in western Crete.*"

For instance, the observations available to Izdebski et al. (2020) and Barjamovic et al. (2019) number in the hundreds. By contrast, our core sample has over 10,000 observations. This enables us to make highly localized inferences and disaggregate the data across various categories ordered by "luxuriousness", while still obtaining reasonably precise estimates.

There is an extensive archaeological demography literature that estimates settlement populations based on pottery and house size data. It is generally acknowledged within this literature that, due to some unidentified parameters in their models such as the per capita propensity to consume pottery or how that would convert into sherd (pottery piece) finds, it is difficult to estimate the raw population of settlements, changes in population or other related statistics (see Bintliff and Sbonias (1999); Chamberlain (2006) and references therein). In our model below, we too do not observe these moments nor do we have a basis to calibrate some parameters, however the data are sufficient in quantity and quality to estimate relative luxury consumption across space in different historical eras with mild assumptions.

We also add to the evidence on sorting in early cities cited in LeRoy and Sonstelie (1983), which focuses on census data from 19th century North American cities. In their paper, the authors build a model with transportation choices. When the rich choose different transportation modes than the poor (e.g. the rich use an automobile and the poor walk), then the rich may choose to live in the suburbs. In addition to the alternative setting, our model complements their work by providing various differing sorting conditions even when the transportation modes for all households are the same and also by explicitly including multiple consumption goods in a urban model. Finally, our work contributes to the literature on the economic history of Ancient Greece, see e.g. Amemiya (2014).

Section 2 provides the appropriate historical and geographical context for the island and a summary of the archaeological project that our data is sourced from. In Section 3 we explain how we infer consumption from the data, while Section 4 uses these measures to estimate spatial gradients relative to the centers of economic activity. Section 5 builds a monocentric agglomeration model that our empirical gradient estimates are consistent with, and Section 6 concludes.

## 2 The island and data

The data were collected from the Greek island of Antikythera (see Figure 1), in a project described in detail in Bevan and Conolly (2014). An overview of the history and geography of the island can be found in Bevan and Conolly (2012), an excerpt from which reads: *"Antikythera is a small island (ca. 20.8 sq.km) in the Mediterranean Sea. Despite being comparatively remote from larger land masses in Mediterranean terms, it lies along important*

*routes of maritime interaction between the Peloponnese and Crete, and between the eastern and central Mediterranean. This geographical position has contributed to its very episodic history of human exploitation stretching back some 7,000 years, but with periods of substantial settlement followed by others of near complete abandonment. Highlights of this long-term history include evidence visits by Neolithic hunters from the Cyclades, Bronze Age farms with cultural links to Crete during the period of the Minoan palaces, a fortified settlement of Hellenistic pirates, a clutch of Late Roman communities, some glimpses of Middle Byzantine settlement and a recolonisation by west Cretan families in the late 18th century AD."*

Between 2005-07, ASP conducted an intensive pedestrian survey of the island. The uniqueness of this exercise lay in the coverage of an entire island in a uniform manner with intensive survey methods.[6] As a result, the data offer a remarkable level of detail in both the individual finds and their precise spatial locations.

We focus on pottery in our study. We do this for several reasons: it is by far the largest type of artefact found in the ASP data; with a few notable exceptions, remnants of building structures were not in the data. A variety of quality of pottery was used by households in these eras for cooking, storage and display (among others) (Sparkes, 2013), which allows us to potentially measure spatial differences in the consumption of quality. And though some types of pottery were more valuable than others, in general pottery was not particularly expensive (Gill, 1988, 1991).[7] Almost all households in these eras likely possessed some pottery and so the pottery remains are potentially an indication of all settlement activity.

We interpret the pottery finds as evidence of consumption rather than production. Bevan and Conolly (2013) report finding no evidence of any kilns on the island for any of these periods (or, indeed, after). And while coarse pottery could have been home-produced using a bonfire instead of a kiln (Greene, 1992; Sparkes, 2013), it is likely that most if not all (especially fineware) pottery found on the island from these periods was acquired from "passing ships" (Bevan and Conolly, 2013).

In the data, each piece of pottery is given a classification by Bevan and Conolly (2014)

[6] Quoting from the description in Bevan and Conolly (2012) *"...the entire island was fieldwalked in parallel lines 15-m apart. For certain interesting or problematic surface artefact scatters (particularly those of prehistoric date) this stage-one survey was followed by more detailed stage-two collections on a 10×10-m grid. In terms of digital recording, this project was unusual for the detail of its treatment of the location, dating and other attributes of its artefacts. First, all artefacts and standing structures were entered individually in a database (with information on shape, size, decoration, fabric, date, location, etc.), rather than in aggregate, and these records were all the result of sustained laboratory study rather than decisions in the field. Second, the project sought to standardise the recording of the spatial location of all material culture, regardless of the survey method by which it was observed, such that all finds and observations had an effective spatial precision of ±10 m. Third and finally, it was the first substantial fieldwork project, to our knowledge, to adopt a probabilistic approach to assigning dates to individual collected artefacts."*

[7] In fact, according to Gill (1988, 1991), pottery's presence on merchant ships owes as much to its role as a space-filler or ballast than to its trade value, with Vickers and Gill (1994) also describing pottery as "saleable ballast". Nevertheless the authors themselves regard the latter terminology as troublesome, and this description has also has been criticized by Boardman (1996).

according to its fabrication or thickness: "Fine", "Medium" or "Coarse" in the former case and "Thick", "Medium" and "Thin" in the latter case. In our analysis we combine the "Medium" and "Thin" categories into a single "Non-Thick" category. In addition, for each piece of pottery Bevan and Conolly (2014) assign a probability to it belonging to a particular chronological phase, using methods in Bevan et al. (2013).[8] The use of quantity and variety of pottery by archaeologists for making economic inferences is widespread. See Greene (2005) for examples, including inferences related to trade and the spread of technology and processes.

Our study focuses on three major historical periods in the history of Antikythera: the Minoan period, the Hellenistic period and the Late Roman period. The Minoan period covers the time period between 2700-1200 BC when Antikythera was influenced by the Cretan civilization. The Hellenistic period covers 325 BC-0 AD, while the Late Roman period covers 350 AD-650 AD. We choose these three distinct time periods for our study because of the vastly different characteristics of settlement observed on Antikythera during them, and because the island seemed to be relatively abandoned for large spells between these periods. Antikythera is well-known in the archaeological literature for exhibiting a high degree of historical variance in its settlement. Bevan et al. (2006) describe this phenomenon as one of "rollercoaster demographics".

For the purposes of our study we highlight several elements of the island's history. The Minoan period is dominated by "cultivators" living in the fertile central part of the island who may have colonized the island from its larger neighbor, Crete. In this period many large settlements in ancient Greco-Near East were politically, economically and socially centered around "palaces". Palace-based elites in some places oversaw redistribution of goods and organized production. Crete is a prominent example. However, there is no evidence of a palace or similar structure on Antikythera during this period. After the Minoan period, archaeologists have yet to find "good evidence... for much activity;" (Bevan et al. (2006)) in other words, it may have been abandoned (a situation comparable to its current lightly inhabited state) for an extended period of time. This abandonment would be consistent with general demographic and economic decline throughout the region following the destruction of most palaces from fires or other disasters.

During the Hellenistic period Antikythera was resettled but in a different part of the

[8]The phases are: Middle to Late Neolithic (pre-4500 BC), Final Neolithic to Early Bronze 1 (ca. 4500-2700 BC), Early Bronze 2 (ca. 2700-2200 BC), Cretan late Prepalatial (ca. 2200-1950 BC), First Palace or Cretan Protopalatial (ca. 1950-1750 BC), Second Palace or Cretan Neopalatial (ca. 1750-1450 BC), Third Palace or Mycenaean (ca. 1450-1200 BC), Post Palatial to Protogeometric phases (1200-900 BC), Geometric phase (900-600 BC), Archaic phase (600-500 BC), Classical phase (500-325 BC), Hellenistic phase (325-0 AD), Early Roman phase (0-200 AD), Middle Roman phase (200-350 AD), Late Roman phase (350-650 AD), Early Byzantine phase (650-900 AD), Middle Byzantine phase (900-1200 AD), Early Venetian phase (1200-1400 AD), Middle Venetian phase (1400-1600 AD), Late Venetian phase (1600-1800 AD), Recent phase (1800-present), any other chronological phase.

island. The island was, as Bevan et al. (2006) notes, "dominated by a fortified town at a strategic position on its northern coast, overlooking a natural protected harbor. Documentary evidence suggests its role in piracy. Our survey indicates the presence of one or two other Hellenistic scatters on the island" which may have been "in some manner, part of the logistical and economic agenda of the fortified town itself."

Subsequent to the sack of this fortified town by the Romans in 69-67 BC the island once again suffered a near abandonment before settlements appeared in and around the town of Potamos and in the fertile area of the island culminating in a peak in the Late Roman era. Thus, Antikythera appears to have been primarily an agricultural economy with atomized dwellings in Minoan times, a maritime economy in Hellenistic times and a combination of maritime and agrarian in Late Roman times. Bevan et al. (2006) notes that the agrarian settlements in the Late Roman era were rather less amorphous than in the Minoan era, nucleating into hamlets.

Thus our choice of the three time periods is motivated precisely by archaeological and historical observations: these three periods correspond to distinct and prosperous phases in Antikythera's history. The discontinuity in settlement also makes the task of distinguishing between historical phases much simpler; in the words of Bevan et al. (2006) the discontinuity makes the landscape *"a less complicated palimpsest than in most other Mediterranean locations."*

Our interest lies in estimating consumption gradients relative to a "central" location, in the sense of being the center of economic activity. This center changed across the three time periods we focus on. Figure 2 shows the island in its entirety, together with the location of the fertile center of the island, where most economic activity took place during the Minoan era and which also constituted a major economic settlement in the Late Roman era, the Kastro (Greek for castle) in the northern part of Antikythera, which was the economic hub during the Hellenistic heyday of the island, and the port of Potamos, which saw considerable economic activity in the Late Roman epoch. Potamos is now the largest modern-day settlement on Antikythera.

Not much is known with certainty about the urban geography of the socio-political landscape on Antikythera during these time periods. However, more generally, Ancient Greece and Crete featured many villages or towns populated by, among others, farmers who walked out to their family plots (*kleros*) (Andrews, 2012). Cities and towns, particularly by Hellenic times, were likely socioeconomically stratified and the presence of urban rental property, local amenities like bath-houses and gymnasia and multi-family housing was not uncommon (Davies, 2007). Normal houses, even in Minoan times, could be substantial in size, with multiple floors. Intriguingly, one estimate of the median size in Minoan times near the palatial center of Crete is 130 $m^2$ with estimates of sizes declining with distance from

the palace (Morris, 2007). This would be consistent with our model under our preferred calibration when local transport costs were predominantly in time.

The amount of trade of goods and services within a settlement seems to have varied greatly by period and place, though much of this is speculation. In Minoan times, many households (which could be large and hold multiple families of various ranks) aimed for a large degree of self-sufficiency (Morris, 2007). After all, *Oikoi*-nomics was the art of efficiently managing the household. Even then, however, and certainly by the Hellenistic era, families with access to villages would routinely go into their centers for specialist or high-quality needs (Morris, 2007).

# 3 Measuring consumption

In this section we detail how we measure consumption gradients using the ASP data set. Our method covers the island of Antikythera with a fine grid of cells, and then measures pottery counts and hence consumption for each of these cells. The cells are approximately 633 sq. meters each, and Table 1 provides details about how many of these cells contain finds. The exercise is conducted separately for all three eras of settlement, although based on our initial analyses we refine our gridding strategy for the Hellenistic era, as we detail below.

There are a number of potential challenges in "counting" pottery. The survival rates of sherds can vary by composition, location and era of use (Morris, 2007). This can make it difficult to draw inferences about, say, how raw population numbers might have varied across time based solely on pottery. For these reasons, we will seek to only draw inferences from the share of sherds by type in a particular location and from a particular period. As long as the survival rates of sherds do not differentially vary by type across locations, then our inferences are valid for our purposes.[9]

## 3.1 Measuring quality

Pottery was used during these time periods in a wide variety of ways for everyday life. It was used for household storage, cooking, dining and for display items (i.e. "art"), among others. In addition to their size and shape, pottery sherds (pieces) can reveal a lot about the ware they were a part of through their glazing and clay composition, for example. We use two widely accepted dimensions to measure quality: coarseness of the fabrication material of the pottery and the thickness of pottery pieces, with finer and thinner being more luxurious.

[9]For instance, if relative survival rates of fine vs coarse pottery from the Hellenistic period varied by location within our settlement, then that could bias our results. We know of no reason why this should be true.

This is consistent with evidence of the significance of pottery in ancient Greece and that finer fabrication and thinner walls, which generally required relatively capital intensive productive methods (i.e. kilns) and higher skilled labor, correlated with higher quality pottery wares (Chankowski, 2013).

Boardman (1988) discusses the importance of the pottery trade in ancient Greece by studying its value relative to other commodities. In his seminal encyclopedic account of ancient Roman life, Pliny the Elder relates an anecdote about a competition between a master and an apprentice to make the thinner earthenware, the delicate results of which are displayed in a temple. He further describes the Greek island of Cos to be particularly famous for their thin pottery, see p. 337, article 161, in Pliny the Elder (1991). Clark et al. (2002), p. 77, discuss the especially fine Attic and Corinthian clays, and indeed such Greek pottery wares were important import goods in neighboring regions such as Palestine and Phoenicia, often inspiring cheaper local imitations (Rosenthal-Heginbottom, 1995; Berlin, 2015).[10]

Quality distinctions along these dimensions are often made in the literature (Hodder, 1974a,b; Greene, 2005; Kron, 2012). This is consistent with our view that "luxury" goods in our model are not luxurious in the typical sense of being extremely expensive but not indispensable (such as a gold vase, affordable only for the very cream of the Athenian elite in Hellenistic times), but rather those whose consumption share elasticity is increasing in total goods spending. In this way we exploit the variegated bundle of pottery that was consumed in this era.[11]

Evidence on prices of pottery from these periods points to non-trivial price dispersion between types of pottery. While a simple cup sold (perhaps wholesale) by a mass producer near Athens might fetch around 1/100th of a low-skilled Athenian laborer's wage, prices for finer vases and amphorae (storage vessels) could easily eclipse their daily wage (Boardman, 1988). Trade costs were likely considerable, meaning the costs to Antikytherians relative to their daily production were likely considerably higher (Boardman, 1988; Bresson and de Callataÿ, 2013; Chankowski, 2013).[12] Some basic pottery may have been home-produced

[10]Local imitations are not likely in our setting because, as we note, there seem to have been no kilns on the island during these periods.

[11]There has been a vigorous, even rancorous, debate in archaeology about the importance of fine pottery wares in ancient Greece. Vickers and Gill (1994) strongly argue against the value imputed to pottery by modern constructs, instead claiming that truly luxurious items were made of gold and silver. This view has been vehemently contested by Boardman (1996), amongst many others, and challenged more recently in Williams (2013) and Tsingarida (2013). A central argument is that gold and silver were necessarily much more expensive than any form of pottery, but this does not make certain types of pottery inexpensive for the majority of the populace. Cook (1987) also provides some arguments against the view of Vickers and Gill (1994) that some ancient Greek pottery techniques explicitly attempted to replicate metalwork. We do not claim a true luxury value for the pottery in our work. Luxury has a specific meaning for us that is somewhat distinct from these debates.

[12]Indeed there is evidence that the ceramics in ships' holds, far from being mere ballast (Vickers and Gill,

by people on the island using household fires or bonfires to fire the clay. Such items would have been low in quality. In any case, given that around 70 percent of daily wages typically went towards food alone, the income elasticity of demand (and therefore variation thereof) for pottery goods was likely much higher than would be for similar goods nowadays (von Reden, 2007).

Furthermore, the types of fine pottery found in particular periods and places in the Ancient world varied greatly in a way that was not merely reflective of changes in technology. Local tastes played a great role in determining demand for, say Athenian fine pottery versus Corinthian fine pottery and merchants evidently responded to regional variation in tastes by supplying the goods that were in greater demand (Osborne, 2007). The ASP data sometimes contain identifying information beyond merely "fine", such as potential origin, though differentiating along these additional dimensions would be difficult and estimates on such a basis would likely lack power. That said, the literature's identification of the greater role of "style" in the fine pottery is consistent with our treatment of fine (or thin-walled) pottery as a relative luxury.

Given our data on both quantity of pottery as well as quality (fine, medium, coarse or thick, non-thick), we already have a natural separation of consumption quality. Raw total pottery counts may be taken to be proxies for total consumption. Meanwhile, relative gradients of pottery counts by quality can measure the relative consumption of higher quality goods by location.

More precisely, suppose that in a given cell $\mathcal{C}$ in era $\mathscr{E}$ we observe $p^{\mathscr{E}}_{\mathcal{C},f}, p^{\mathscr{E}}_{\mathcal{C},m}$, $p^{\mathscr{E}}_{\mathcal{C},c}$, $p^{\mathscr{E}}_{\mathcal{C},t}$ and $p^{\mathscr{E}}_{\mathcal{C},nt}$ pieces of fine, medium coarse, thick and non-thick pottery, respectively, with each individual piece denoted with $i$ subscript. Denoting by $\pi^{\mathscr{E}}_{i,f}$ the probability of the $i$th piece of fine pottery belonging to era $\mathscr{E}$ as computed by Bevan et al. (2013), with similar probability notations for other pottery qualities, the probability-weighted consumption measure in cell $\mathcal{C}$ is

$$P^{\mathscr{E}}_{\mathcal{C}} = \sum_{i=1}^{p^{\mathscr{E}}_f} \pi^{\mathscr{E}}_{i,f} p^{\mathscr{E}}_{\mathcal{C},i,f} + \sum_{i=1}^{p^{\mathscr{E}}_m} \pi^{\mathscr{E}}_{i,m} p^{\mathscr{E}}_{\mathcal{C},i,m} + \sum_{i=1}^{p^{\mathscr{E}}_c} \pi^{\mathscr{E}}_{i,c} p^{\mathscr{E}}_{\mathcal{C},i,c} = \sum_{i=1}^{p^{\mathscr{E}}_t} \pi^{\mathscr{E}}_{i,t} p^{\mathscr{E}}_{\mathcal{C},i,t} + \sum_{i=1}^{p^{\mathscr{E}}_{nt}} \pi^{\mathscr{E}}_{i,nt} p^{\mathscr{E}}_{\mathcal{C},i,nt}, \qquad (1)$$

$\mathscr{E} \in \{\text{Minoan, Hellenistic, Late Roman}\}$, while raw consumption measures can be constructed without the use of probability weighting.

In Figures 3-7, we illustrate the distribution of pottery over the island, separately for each era. In each figure, the panels correspond to the Minoan, Hellenistic and Late Roman eras respectively from left to right. Table 1 presents some summary statistics about the data, and these are visualized in the presented maps. Examining Figure 3, the 5,497 coarse

1994), were valuable enough to be used as collateral for loans by merchants (Chankowski, 2013).

pottery pieces in the Minoan era seem mostly concentrated around the fertile center of the island but in clumps that belie the presence of a true quasi-urban settlement, while the 32 coarse pottery pieces that correspond to the Hellenistic era are almost entirely concentrated around the port of Kastro. The 49 pieces of coarse for the Late Roman era are more broadly scattered but noticeably absent from the Potamos area. Thus, we already see some evidence of the vastly changed economic structure of the island across eras.

The comparison between medium pottery quantities is somewhat closer: 906 Minoan pieces, 818 Hellenistic pieces and 1173 Late Roman pieces. We plot these finds in Figure 4, noticing a similar pattern to the one observed for coarse pottery, with one exception. Examination of the rightmost panel reveals an abundance of medium grade pottery in the Potamos area in the Late Roman era, while coarse pottery was noticeably absent. Nevertheless, there are further scatters that suggest the presence of some prosperous farmsteads in the "hinterland" of the island even while the bulk of economic activity takes place around the port. Indeed, in Figure 5, we plot the finds of fine pottery and find much the same patterns. The overall distributions between eras still reflects the stark contrasts observed earlier, and the fact that there are 856 (1369) pieces of fine Hellenistic (Late Roman) pottery as opposed to just 226 Minoan pieces provide some evidence of the technological advances that accompanied the structural economic changes on the island.

Figure 6 shows a similar patter to the ones discussed above for pottery qualities: the 516 Minoan pieces are distributed in clumps around the fertile center, while the Kastro accounts for most of the 104 thick Hellenistic pieces. The 406 Late Roman pieces are bi-modally distributed around Potamos and the fertile center. Moving to non-thick pottery distributions, Figure 7 shows the same clumping pattern for the 6113 Minoan pieces. For the Hellenistic era we observe a cluster of non-thick pottery to the south of the Kastro, which also corresponds to a cluster of fine pottery observed in Figure 5. This hot-spot of "luxury" consumption is the location of a temple of Apollo, see Figure 6.8, p. 138 of Bevan and Conolly (2013). The Late Roman era again exhibits bi-modality in non-thick pottery distribution.

The eyeballing exercise in the previous paragraph can be improved by using the cell-wise consumption measures defined in equation (1) to obtain a smooth estimate of consumption over the island by plotting kernel density estimates. The results are displayed in Figures 8-10. The color scheme runs low-medium-high as green-yellow-red and is buttressed further with vertical heights measuring consumption densities. The figures are plotted in a northeasterly perspective from an elevated southwestern viewpoint. We observe the concentrations of consumption in the areas we saw previously in both eras. As the earlier figures suggested, the consumption distributions in the Minoan and Late Roman eras are substantially less skewed than the Hellenistic distribution. The latter is quite distinctive in the exclusivity of

economic activity around the Kastro in a fairly small radius, and this factor will influence our choice of gridding strategy for this era.

# 4 Consumption profiles

## 4.1 Consumption relative to center of economic activity

Our analysis in the previous section indicates the presence of consumption gradients. In this section we estimate how pottery finds change with distance and discuss our findings in relation to the figures we have already presented. We fit regression models of the type $y = m(x)+\epsilon$, where $m(\cdot)$ is an unknown nonparametric function of distance $x$ from the economic center and $y$ is the specific pottery series we use for a particular analysis. We use the series or sieve estimation method which approximates the regression function $m(x)$ by a linear combination of, say, $\ell$ basis functions, which we choose to be splines. Thus the regressions estimated are of the form $y = \sum_{j=1}^{\ell} s_j(x)\beta_j + e$, where $e = \epsilon + m(x) - \sum_{j=1}^{\ell} s_j(x)\beta_j \equiv \epsilon + r(x)$, say. The remainder $r(x)$ is the approximation error which is negligible under various technical conditions involving the smoothness of $m(\cdot)$, see e.g. Chen (2007). The estimation is implemented using the GAM package in R.

As we will see below, nonparametric fits allow us to capture nonlinearities in the profiles that reflect economic features of the island's consumption distribution as well as the island's geography and topography. Solid lines correspond to the fitted profile while asymptotic 95% confidence intervals (i.e. based on a standard normal critical value of 1.96) are traced out with dashed lines in each figure. Distance from the economic centers, defined as the fertile center, Kastro and Potamos in the Minoan, Hellenistic and Late Roman eras respectively, is in meters on the horizontal axes. For the Late Roman era we will also examine the situation where two separate economic centers, Potamos (maritime) and the fertile center (agrarian) are considered.

### 4.1.1 Absolute consumption profiles

Estimated profiless of total consumption, obtained from the probability-weighted formula of equation (1) and its unweighted version are displayed in Figure 11. Plotted in each figure are spline based nonparametric fits; red lines correspond to the probability-weighted measure as in equation (1) while the green lines correspond to the unweighted versions. The origin is a center of economic activity for each era: the fertile heart of the island for the Minoan era, Kastro for the Hellenistic era and the fertile heart again for the Late Roman era.

Nonlinearity in the profiless is captured by the nonparametric fits, which show secondary humps in the consumption profiles in the Minoan and Late Roman eras. The Minoan hump

is a smaller peak than the peak at the origin and corresponds to other fertile areas of the island. The hump is more pronounced (corresponding to Potamos), and the profiles generally less steep, in the Late Roman era. Assuming a constant survival probability of pottery across eras as discussed in second paragraph of Section 3, this can be interpreted as reflecting the more equitable distribution of economic activity on the island during this phase, as both maritime and agrarian activity co-existed. Thus in our analysis of relative consumption gradients below, we analyze the two centers as separate economic hubs. On the other hand, the nonparametric fits for the Hellenistic era essentially plummet to zero at just about one kilometer from Kastro, reflecting the concentrated nature of economic activity in this era.

The slight upwards bend observed in both fits for the Hellenistic era at large distances could be ascribed to the presence of isolated communities in the coastal areas of the island, as seen be the presence of small quantities of pottery in some coastal areas in the leftmost panels of Figures 3-5. Note though that confidence bands become wide at the extremities of distance (as in the other two era considered), so this upwards bend could reflect the imprecision of these estimates due to sparse data.

#### 4.1.2 Relative consumption profiles

From our examination of absolute consumption profiles above we see no qualitative difference between considering probability weighted and unweighted pottery quality counts, so we focus on the latter. Plots with the former lead to no difference in interpretations. Furthermore, the Hellenistic gradients show the highly local nature of pottery concentration in that era. Thus, in order to better utilize the data and obtain clearer insights we adopt a finer spatial resolution for this period. We do this by gridding the data with cells of approximately 70 sq. meters, as compared to the 633 sq. meters used earlier. Such 'zoomed-in' smaller cells are not very useful in the other two eras with pottery scatters ranging over a much wider area, but are feasible and indeed useful in the Hellenistic era. Table 1 includes summary statistics for the Hellenistic era with this finer resolution.

Using these grids, we fit a non-parametric spline to the logarithm of pottery counts in each cell by quality, on distance from the economic center. As our goal is to measure the relative consumption of each type of pottery across space, we wish to avoid unsettled regions contaminating any inference, so we exclude cells which contain no pottery of any type. As there remains some cells which contain some types of pottery but not all types of pottery, for our logarithms, we take the logarithm of $1+p^{\mathscr{E}}_{\mathcal{C},q}, q =$ Fine, Medium, Coarse, Thick or Non-Thick, where each $p^{\mathscr{E}}_{\mathcal{C},q}$ series is normalized to [0,1] by dividing by its largest value. Thus in this section our nonparametric regression estimates take $y = \log\left(1 + p^{\mathscr{E}}_{\mathcal{C},q}\right)$.

Figures 12- 15 plot the fitted nonparametric regression curves, which are normalized to

be unity at the origin. In each figure the upper panel corresponds to consumption of coarse, medium and fine pottery (green, red and blue lines, respectively) while the lower panel shows thick and non-thick pottery (magenta and orange lines, respectively). As discussed above we present separate plots relative to the two distinct centers observed in the Late Roman era. While Potamos and the Kastro are distinct economic centres, the fertile center of the island is not as sharply defined as a condensed ancient fortified town. Thus, we present figures where the origin for Potamos and the Kastro corresponds roughly to the center of the town, while for the fertile center (both in the Late Roman and Minoan era) this point is taken to lie more generally within farmland. This implies that the region of highest consumption need not lie at zero (or very small) distance in the plotted figures, as is the case for Potamos and the Kastro. We stress that one may set the origin arbitrarily on the island in any era and then visually examine consumption profiles as they approach the highest consumption 'hump' from either side. However, since centers are so transparently defined for Potamos and the Kastro we pin these origins to virtually coincide with the point of highest consumption.

For settlements such as Potamos and the fertile center in the Late Roman era and the Kastro in the Hellenistic, consumption of fine and medium pottery decreases noticeably from the settled center (approximately the cell with the highest total pottery count). Meanwhile coarse pottery consumption remains relatively flat with distance. For the Hellenistic era, this manifests itself relative to the point of highest consumption at the origin (Figure 12). On the other hand, the upper panel of Figure 14 shows a hump for both fine and medium pottery corresponding to the fertile center, with profiles increasing (decreasing) as one gets closer to (farther from) the hump, while coarse pottery shows no such pattern. This is consistent with greater "luxury" consumption in the economic center, as we emphasized in the previous paragraph. This pattern is similar to ones found in various Roman-Britain towns in Hodder (1974a,b). The upward bend in fine pottery for the Hellenistic era at the farthest distance is due to the presence of the aforementioned coastal temple of Apollo, which does not correspond to an economic settlement. In addition, Johnston et al. (2012) points out the existence of graveyard at a similar distance from the Kastro walls that would typically have some fine pottery buried with the deceased; see Figure 2 therein and the discussion on p. 248.

Similar patterns are observed in the thick and non-thick pottery gradients: in the Hellenistic era (lower panel of Figure 12) non-thick "luxury" pottery consumption exhibits a sharp negative gradient while thick pottery consumption remains relatively flat. For the fertile center settlement in the Late Roman era (lower panel of Figure 14) consumption of non-thick "luxury" pottery increases more rapidly than that for thick pottery as the center of the settlement is approached. This is again consistent with greater "luxury" consumption in the economic center. Similarly, for Potamos in the Late Roman era (lower panel of Fig-

ure 13) we see a marked difference in the gradients of pottery quality consistent with the discussion in the previous paragraph.

Contrary to the time periods discussed above, the Minoan era featured single family farmsteads with no discernible center of economic activity, as discussed by Bevan and Conolly (2013), p. 124-126. It thus constitutes a more primitive economy and acts as a kind of informal placebo. We have no formal alternative hypothesis about the distribution of income (and thus pottery) in this era. As a mostly subsistence agrarian settlement, it is likely that income variations across most farmsteads were small, in which case the undulations of the consumption profiles for all qualities of pottery may roughly parallel each other.

As the preceding discussion stressed, in the other eras that we consider these gradients are markedly different across pottery types with consumption of higher quality pottery declining more steeply with distance from the economic centre. On the other hand, in the upper panel of Figure 15 fine and coarse pottery move in tandem while medium pottery's gradient is less steep than coarse's. In the lower panel we observe an initial flat gradient for thick pottery as opposed to a steep slope for the non-thick pottery near the "peak" settlement (the area with the most pottery during this era), but at a distance of 1000m both profiles behave in almost identical fashion indicating no detectable difference in the patterns of "luxury" versus non-"luxury" consumption across most of the island at this time.

We also compute some correlations that augment our visual analysis. Table 2 shows the correlation between $\log\left(1+p^{\mathscr{E}}_{\mathcal{C},q}\right)$ and $\log\left(P^{\mathscr{E}}_{\mathcal{C}}\right)$, i.e. between pottery quality (coarseness or thickness) and total consumption within cells in different eras. We observe that there is little difference in the pattern of these correlations for the Minoan era that suggest a decline in luxury consumption with a decline in total consumption: all correlations are strong. On the other hand, for the Hellenistic and Late Roman eras the correlations are clearly stronger for the higher grades of pottery (whether in quality or thickness), implying that a higher share of luxury consumption is higher associated with higher consumption. This is consistent with the sorting predicted by our model below. The equality of the correlations for fine and medium pottery in the Late Roman era is simply the result of chance.

As the results discussed above show, our empirical evidence for sorting varies with settlement patterns. An interesting question is whether these differences have counterparts in the historiography of the region. Indeed, archaeologists have linked settlement patterns with specific agricultural practices, and these links match what we observe in the Minoan and Late Roman eras in particular (recall that the Hellenistic era settlement was mainly not devoted to agriculture).

As discussed by Davis (1991), p. 138-139, Halstead (1987) classifies Mediterranean agriculture into *traditional* and *alternative* practices. The traditional system featured nucleated settlements involving long travel time to fields and a form of production with scattered land

holdings as well as large livestock herds often grazing in uplands, thereby depositing manure far from cultivated fields. This is similar to the patterns we observe in the Late Roman era, when at least part of the island was devoted to agriculture. On the other hand, the older, alternative practice involves smaller herds that grazed on fields adjoining a homestead only. There was little surplus yield to support non-farming households and therefore little need for a market. As a result, settlements were more dispersed. These dispersed consumption patterns are the patterns we observe in the Minoan era. Thus our empirical evidence is consistent with this archaeological historiography: we find sorting patterns consistent with subsistence economies in the Minoan era and relatively more market oriented economies in the Hellenistic and Late Roman eras.

### 4.2 Relative consumption profiles without amphorae: a robustness check

Amphorae were a specific type of pottery used as containers for storage. As such, they appear to comprise a type of "necessary" good even if their fabrication may differ by coarseness or thickness. We wish to check if our empirical results are robust to the exclusion of amphorae. To do this we exploit information on the type of pottery that a particular fragment originates from. Note that such information is not always available in the data as this type of classification is inherently challenging with some fragments, especially small ones. On the other hand, coarseness and thickness can always be measured regardless of fragment characteristics. The quantity of amphora fragments is negligible in the Minoan era (40 out of 6629) so we do not present results for this.

For the Hellenistic era (706 amphora fragments out of 1706 in total), we see from Figure 16 that the coarseness gradients are robust to the removal of amphora fragments but the influence of the temple of Apollo increases. This suggests that concentration of fine fragments in the temple come from items other than amphorae. The thickness gradients are also robust, although the negative gradient in non-thick pottery is now less pronounced. For the Late Roman era (406 amphora fragments out of 2591), we also observe in Figures 17 and 18 that both coarseness and thickness gradients are robust to the removal of amphora fragments.

### 4.3 Summary of empirical findings

Our empirical findings indicate the presence of quality-differentiated pottery consumption gradients relative to economic centres of activity in two of the three eras that we have considered. In particular higher quality goods exhibit steeper profiles. Both of these eras featured some form of nucleated or proto-urban settlement pattern on the island. On the other hand, for an entirely agrarian settlement pattern we do not find such gradient patterns. The visual patterns are congruous with simple correlation measures of consumption quality

with total consumption. Our findings are also consistent with observations made in the historiography of the region for these time periods. Finally, the results are robust to the exclusion of a type of necessary good in these eras. The next section presents a monocentric model that can reconcile our findings with economic theory.

# 5 A monocentric city model with household heterogeneity and luxury goods

In this section we build a model with households such as might have been found in the Xenophon (Socrates) quote above. Ellickson and Thorland (1995) finds that even relatively small groups of households had little problem agglomerating into nucleated settlements. Our model is one of a monocentric agglomeration with households that are heterogeneous in their ability to transform their time into output. Though the basic AMM model has historically been referred to as a "monocentric city" model, it can of course apply to agglomerations that would not have been considered cities by laymen, archeologists or economists. Indeed none of the settlements in Antikythera would be considered "cities" in any other context. Below we use "city" for ease of exposition, in keeping with typical nomenclature in urban economics. There are a set of consumption goods, land and leisure. Even though the model uses preferences with meaningful consumption and substitution effects from leisure, we are able to obtain some sorting results for the competitive equilibria. We show that when commuting costs are dominated by time costs, as they most likely were on Antikythera during the periods we examine, households sort such that high ability (high income) households live close to the city center. In such case, luxury goods consumption is higher in the city center.

## 5.1 Setup

Households have preferences over a vector of $I$ non-durable consumption goods, land and leisure ($c, a, l$, respectively) denoted by $u(c, a, l)$. Households are endowed with one unit of time which they may use for work, commuting or leisure. We normalize the population to 1. Households are heterogeneous in the productivity of their work time, denoted by $z \sim F_z$, where $F_z$ is the distribution of population abilities with support $Z$ and density $f_z$. A unit of work time is converted into $z$ units of any in a set of non-durable goods $i \in I$. In equilibrium this will mean that the relative price of each good $i$ is the same. We normalize this price to 1.

All households live in a monocentric city and "commute" into the center of the city.[13] Commuting from home a distance $r$ costs $t_1(r)$ in time and $t_0(r)$ in the numeraire good.

[13] We leave unspecified whether this is to consume location based amenities, buy goods or work.

The supply of land at a distance $r$ in the economy is given by the density $f_r : \Re_+ \to \Re_+$.

We assume the initial endowment of land is equal for all households. In competitive equilibrium it must be the case, for each household, that

$$\sum_i c_i + ap(r) + lz \leq \Lambda + z(1 - t_1(r)) - t_0(r) \tag{2}$$

where $p(r)$ is the price of land,

$$\Lambda = \int p(r) f_r(r)\, dr$$

is the total value of land in the city and ((2)) is the household's budget constraint. [14]

## 5.2 A preview of further results

As is well known, completely general results are difficult to obtain for monocentric models with heterogeneity. In the subsequent parts of this section, we assume functional forms for utility and provide some explicit sufficient conditions under those assumptions for when greater concentrations of luxury consumption may be found in settlement centers. Before doing so though, we preview the results in a more general way.

Consistent with our data, households in our model have access to non-durable goods of varying "luxuriousness". We define one good as more luxurious than another if households with higher total non-durable expenditures spend a higher share of their expenditures on the luxury good than households with lower total spending. Thus, our model features an equilibrium where there is a higher share of luxury consumption (relative to other non-durables) wherever the absolute level of non-durable spending is higher. Holding ability fixed, equilibrium total non-durable spending will be higher nearer the center if housing consumption is not too house-price-elastic.

In the setting of our data, most local travel was done by foot. In our model, as in LeRoy and Sonstelie (1983) and others, if local travel costs are chiefly in time rather than goods, more productive households are likely to sort into the settlement center. As these households will have higher total spending, higher luxury shares are found closer to the center.

[14] The nature and forms of property rights and property ownership varied greatly across ancient times (Bedford, 2007; Morris, 2007). For the purposes of the model, the price of land may be thought of as the price of the right to own it or perhaps as a usufruct right. Our results do not depend on which. In other words, $\Lambda$ can be thrown into the sea (or donated to the local temple or cult if they owned the land) rather than remitted to the residents in lump sum.

### 5.3 Preferences

We assume that households have a constant elasticity of substitution preferences over land, leisure and a composite $g : I \to \Re$ of the non-durable goods:

$$u(c, a, l) = \frac{\left(\omega_1 g(c)^{\frac{\varepsilon-1}{\varepsilon}} + \omega_2 a^{\frac{\varepsilon-1}{\varepsilon}} + \omega_3 l^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\gamma\varepsilon}{\varepsilon-1}}}{\gamma}.$$

with $\varepsilon, \gamma < 1$.We assume the composite $g$ is:

$$g(c) = \prod_{i \in I} (c_i - \beta_i)^{\alpha_i} + \sum_{i \in I} \beta_i \tag{3}$$

where $\beta_i \geq 0$ are preference parameters and $\sum_{i \in I} \alpha_i = 1$ with $\alpha_i > 0$.

### 5.4 First order conditions

#### 5.4.1 Non-durable consumption choices

The first order conditions for the household imply that

$$\frac{(c_i - \beta_i)}{\alpha_i} = \frac{(c_j - \beta_j)}{\alpha_j} = v(x)$$

where $v$ is the indirect sub-utility function for preferences $g$ given total spending on non-durable goods $x$. Using the budget constraint for this sub-problem ($x = \sum_{i \in I} c_i$) we get

$$v(x) = x$$

and

$$c_i = \alpha_i (x - \sum_{j \in I} \beta_j) + \beta_i \tag{4}$$

If the goods can be ordered such that $(\beta_i - \alpha_i \sum_{j \in I} \beta_j)$ is decreasing in $i$, than higher $i$ goods are more "luxuriousness." (I.e. the elasticity of good $i$'s consumption share of total good spending $x$ with respect to $x$ is increasing in $i$.)

#### 5.4.2 Consumption expenditures, land, leisure and location

The first order conditions for the rest of the household's problem, using the fact that $g(c) = x$ where $x$ is the amount the household will spend on non-durables, are:

$$\lambda_c = u_c(x,a,l) \tag{5}$$
$$\lambda_c p_r(r) = u_a(x,a,l) \tag{6}$$
$$\lambda_L(r,z) + \lambda_c z = u_l(x,a,l) \tag{7}$$
$$a(r,z)\frac{dp}{dr} = -z\frac{\partial t_1(r)}{\partial r} - \frac{\partial t_0(r)}{\partial r} \tag{8}$$

Equation 8 becomes the Alonso-Muth condition by examining the slope of the bid-rent curves $\Psi(r,z;\bar{u})$. In equilibrium, $\frac{dp}{dr}(r) = \Psi_r(r^*(z),z;u^*)$.

Strict sorting occurs if everywhere:

$$\frac{\partial^2 \Psi}{\partial r \partial z}(r,z) \gtrless 0$$

Subbing in we get that land demand is:

$$a(r,z) = \underbrace{\frac{\Lambda + z(1-t_1(r)) - t_0(r)}{\omega_1\left(\frac{1}{\omega_1}\right)^{1-\varepsilon} + \omega_2\left(\frac{p(r)}{\omega_2}\right)^{1-\varepsilon} + \omega_3\left(\frac{z+\lambda_L(r,z)}{\omega_3}\right)^{1-\varepsilon}}}_{\equiv P(r,z)}\left(\frac{p(r)}{\omega_2}\right)^{-\varepsilon} \tag{9}$$

so

$$\frac{\partial^2 \Psi(r,z)}{\partial r \partial z} = \frac{\frac{dt_1(r)}{dr}}{a(r,z)}\left[\frac{z}{a(r,z)}\frac{\partial a(r,z)}{\partial z} - 1\right] + \frac{\frac{dt_0(r)}{dr}}{(a(r,z))^2}\frac{\partial a(r,z)}{\partial z}. \tag{10}$$

Note that

$$\frac{\partial P(r,z)}{\partial z} \geq 0,$$

strictly so if $1 - t_1(r) > l(r,z)$. Differentiating 9:

$$\begin{aligned}\frac{\partial a(r,z)}{\partial z} &= \frac{1-t_1(r)}{P(r,z)}\left(\frac{p(r)}{\omega_2}\right)^{-\varepsilon} - \frac{\Lambda + z(1-t_1(r)) - t_0(r)}{(P(r,z))^2}\left(\frac{p(r)}{\omega_2}\right)^{-\varepsilon}\frac{\partial P(r,z)}{\partial z} \\ &= a(r,z)\left(\frac{1-t_1(r)}{\Lambda + z(1-t_1(r)) - t_0(r)} - \frac{\partial P(r,z)}{\partial z}\frac{1}{P(r,z)}\right).\end{aligned}$$

Further sorting conditions are difficult to obtain for cases with both time and goods commuting costs. However if we focus on cases where the costs are either time or goods, we can obtain some conditions. The former case is probably a good approximation of routine local transportation costs on Antikythera during ancient times. The latter case, with only goods, is more futuristic than realistic.

*Case* 1. Commuting costs are only in time: $t_0 \approx 0$

**Lemma.** *If $\varepsilon > \frac{1}{1-\gamma}$, higher types live closer to the center and spend more on non-durables and thus spend proportionately more of the their non-durable expenditures on luxury goods.*

*Proof.* The cross-derivative of the bid-rent curve becomes:

$$\frac{\partial^2 \Psi(r,z)}{\partial r \partial z} = \frac{\frac{dt_1(r)}{dr}}{a(r,z)} \left[ \frac{z(1-t_1(r))}{\Lambda + z(1-t_1(r))} - \frac{\partial P(r,z)}{\partial z} \frac{z}{P(r,z)} - 1 \right] < 0$$

where the inequality follows because $\frac{z(1-t_1(r))}{\Lambda+z(1-t_1(r))} < 1$. So the highest types live strictly closer to the city center.

Non-durable expenditures $x(r,z)$ are similarly

$$x(r,z) = \frac{\Lambda + z(1-t_1(r))}{P(r,z)} \left( \frac{1}{\omega_1} \right)^{-\varepsilon}. \tag{11}$$

The first-order condition for expenditures can be rewritten as:

$$\omega_1 (x(r,z))^{-\frac{1}{\varepsilon}} P^{\frac{\gamma\varepsilon-\varepsilon+1}{(\varepsilon-1)(1-\gamma)\varepsilon}} = \lambda_c.$$

If $\gamma\varepsilon - \varepsilon + 1 < 0$ (i.e. if $\varepsilon > \frac{1}{1-\gamma}$) then $\frac{\partial P^{\frac{\gamma\varepsilon-\varepsilon+1}{(\varepsilon-1)(1-\gamma)\varepsilon}}}{\partial z} > 0$,which in turn implies that $\frac{\partial x(r,z)}{\partial z} > 0$. Note that a conventional estimate of risk aversion and elasticity of substitution have $\gamma \approx -1$ and $\varepsilon \approx 0.9$, which would satisfy the inequality. Under the same parameter conditions, $\frac{\partial P^{\frac{\gamma\varepsilon-\varepsilon+1}{(\varepsilon-1)(1-\gamma)\varepsilon}}}{\partial r} < 0$ and then the first-order condition similarly implies that $\frac{\partial x(r,z)}{\partial r} < 0$. Given negative assortative matching on location, the total derivative $\frac{dx(r,z)}{dz} = \frac{\partial x(r,z)}{\partial z} + \frac{\partial x(r,z)}{\partial r}\frac{\partial r(z)}{\partial z} > 0$ follows. Therefore, higher types live closer to the center and spend more on non-durables. Thus there is higher relative luxury consumption in the center. □

*Case* 2. Commuting costs are only in goods: $t_1 \approx 0$.

The cross-derivative of the bid-rent curve then becomes:

$$\frac{\partial^2 \Psi(r,z)}{\partial r \partial z} = \frac{\frac{dt_0(r)}{dr}}{a(r,z)} \left[ \frac{1}{\Lambda + z - t_0(r)} - \frac{\partial P(r,z)}{\partial z} \frac{z}{P(r,z)} \right]$$

Non-durable expenditures $x(r,z)$ are similarly

$$x(r,z) = \frac{\Lambda + z - t_0(r)}{P(r,z)} \left( \frac{1}{\omega_1} \right)^{-\varepsilon}. \tag{12}$$

The first-order condition for expenditures can still be rewritten as:

$$\omega_1(x(r,z))^{-\frac{1}{\varepsilon}} P^{\frac{\gamma\varepsilon-\varepsilon+1}{(\varepsilon-1)(1-\gamma)\varepsilon}} = \lambda_c.$$

As in the case above, if $\gamma\varepsilon - \varepsilon + 1 < 0$ (i.e. if $\varepsilon > \frac{1}{1-\gamma}$) then $\frac{\partial P^{\frac{\gamma\varepsilon-\varepsilon+1}{(\varepsilon-1)(1-\gamma)\varepsilon}}}{\partial z} > 0$ and $\frac{\partial P^{\frac{\gamma\varepsilon-\varepsilon+1}{(\varepsilon-1)(1-\gamma)\varepsilon}}}{\partial r} < 0$ which in turn imply that $\frac{\partial x(r,z)}{\partial z} > 0$ and $\frac{\partial x(r,z)}{\partial r} < 0$. It also implies $\frac{\partial a(r,z)}{\partial z} > 0$ and thus $\frac{\partial^2 \Psi(r,z)}{\partial r \partial z} > 0$, so that households positively sort. However such sorting is not sufficient to determine which types of households spend more on luxuries. Higher land prices close to the center encourage households living there to spend more of their income on non-durables. On the other hand, households living further away are more productive and have higher incomes. Which effect is stronger will depend on parameterizations.

# 6 Conclusion

The extent to which differences in earnings, skills or wealth maps into spatial sorting within cities and thus into, perhaps, differential access to public goods is a fundamental question for urban and public economics (e.g. Glaeser et al. (2008, 2009); Chetty and Hendren (2018)). Modern cities are shaped by amalgam of forces, some present and some historical. Modern transportation networks often are partially molded by historic networks (in part to reduce frictions to rights of way). Modern public goods often have explicit links to the location preferences of past generations (the Louvre and the Frick Museums were formally residences of their patrons). The legacies of past policies, such as red lining, cast long shadows.

Ancient settlements, especially those that were built without meaningful antecedents, offer a different laboratory to test urban economics models. Here we integrate archaeological data from several past settlements into a simple monocentric city model. We show how to infer the spatial distribution of consumption from the data and then how the simple model, calibrated with modern preferences but ancient transportation costs, can match the data.

# References


Amemiya, T. (2014). *Economy and Economics of Ancient Greece*. Routledge.

Andrews, S. (2012). Villages, Greek. In *The Encyclopedia of Ancient History*. Wiley Online Library.

Bakker, J. D., S. Maurer, J.-S. Pischke, and F. Rauch (2020). Of mice and merchants: Trade and growth in the Iron Age. *Forthcoming: The Review of Economics and Statistics*.

Barjamovic, G., T. Chaney, K. Coşar, and A. Hortaçsu (2019). Trade, merchants, and the lost cities of the Bronze Age. *Quarterly Journal of Economics 134*, 1455–1503.

Bedford, P. (2007). The Persian Near East. In W. Scheidel, I. Morris, and R. P. Saller (Eds.), *The Cambridge Economic History of the Greco-Roman World*, pp. 302–330. Cambridge University Press.

Berlin, A. M. (2015). Hellenistic period. In S. Gitin (Ed.), *The Ancient Pottery of Israel and its Neigbors from the Iron Age through the Hellenistic Period: Volume 2*, pp. 629–672. Israel Exploration Society.

Bevan, A. and J. Conolly (2012). Intensive survey data from Antikythera, Greece. *Journal of Open Archaeology Data 1:e3*, 1–4.

Bevan, A. and J. Conolly (2013). *Mediterranean Islands, Fragile Communities and Persistent Landscapes: Antikythera in Long-Term Perspective*. Cambridge University Press.

Bevan, A. and J. Conolly (2014). The Antikythera Survey Project: https://www.ucl.ac.uk/asp/en/intro.shtml.

Bevan, A., J. Conolly, C. Hennig, A. Johnston, L. Spencer, and J. Vroom (2013). Measuring chronological uncertainty in intensive survey finds: A case study from Antikythera, Greece. *Archaeometry 55*, 312–328.

Bevan, A., J. Conolly, and A. Tsaravopoulos (2006). The fragile communities of Antikythera. *Archaeology International 10*, 32–36.

Bintliff, J. and K. Sbonias (Eds.) (1999). *Reconstructing Past Population Trends in Mediterranean Europe (3000 BC-AD 1800)*, Volume 1, The POPULUS Project. Barker, G. and Mattingly, D. (Eds.). Oxbow Books.

Boardman, J. (1988). Trade in Greek decorated pottery. *Oxford Journal of Archaeology 7*, 27–33.

Boardman, J. (1996). Crafty Arts - M. Vickers, D. Gill: Artful Crafts. Ancient Greek Silverware and Pottery. *The Classical Review 46*, 123–126.

Bresson, A. and de Callataÿ (2013). The Greek vase trade: Some reflections about scale, value and market. In A. Tsingarida and D. Viviers (Eds.), *Pottery Markets in the Ancient Greek World (8th-1st Centuries B.C.): Proceedings of the International Symposium held at the Universite Libre de Bruxelles 19-21 June 2008*. CReA-Patrimoine.

Brown, A. E. and H. L. Sheldon (1974). Highgate Wood: The pottery and its production. *London Archaeologist 2*, 222–31.

Brueckner, J. K. and S. S. Rosenthal (2009). Gentrification and neighborhood housing cycles: Will America's future downtowns be rich? *The Review of Economics and Statistics 91*, 725–743.

Brueckner, J. K., J.-F. Thisse, and Y. Zenou (1999). Why is central Paris rich and downtown Detroit poor? *European Economic Review 43*, 91–107.

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

Chankowski, V. (2013). La céramique sur le marché: l'objet, sa valeur et son prix. Problèmes d'interprétation et de confrontation des sources. In A. Tsingarida and D. Viviers (Eds.), *Pottery Markets in the Ancient Greek World (8th-1st Centuries B.C.): Proceedings of the International Symposium held at the Universite Libre de Bruxelles 19-21 June 2008*. CReA-Patrimoine.

Chen, X. (2007). Large sample sieve estimation of semi-nonparametric models. In J. Heckman and E. Leamer (Eds.), *Handbook of Econometrics*, Volume 6B, Chapter 76, pp. 5549–5632. North Holland.

Chetty, R. and N. Hendren (2018). The impacts of neighborhoods on intergenerational mobility I: Childhood exposure effects. *Quarterly Journal of Economics 113*, 1107–1162.

Clark, A., M. Elston, and M. Hart (2002). *Understanding Greek Vases: A Guide to Terms, Styles and Techniques*. Getty Publications.

Cook, R. (1987). 'Artful Crafts': A Commentary. *Journal of Hellenistic Studies 107*, 169–171.

Davies, J. (2007). Classical Greece: Production. In W. Scheidel, I. Morris, and R. P. Saller (Eds.), *The Cambridge Economic History of the Greco-Roman World*, pp. 331–361. Cambridge University Press.

Davis, J. L. (1991). Contributions to a Mediterranean rural archaeology: Historical case studies from the Ottoman Cyclades. *Journal of Mediterranean Archaeology 4*, 131–215.

Duranton, G. and D. Puga (2015). Chapter 8 - Urban Land Use. In G. Duranton, J. V. Henderson, and W. C. Strange (Eds.), *Handbook of Regional and Urban Economics*, Volume 5 of *Handbook of Regional and Urban Economics*, pp. 467 – 560. Elsevier.

Ellickson, R. C. and C. D. Thorland (1995). Ancient land law: Mesopotamia, Egypt, Israel. *Chicago Kent Law Review 71*, 321–411.

Fretz, S., R. Parchet, and F. Robert-Nicoud (2017, November). Highways, market access, and spatial sorting. CEPR Discussion Papers 12437.

Fujita, M. (1989). *Urban Economic Theory: Land Use and City Size*. Cambridge University Press.

Fulford, M. (1987). Economic interdependence among urban communities of the Roman Mediterranean. *World Archaeology 19*, 58–75.

Gibson, D. and G. Lucas (2002). Pre-Flavian kilns at Greenhouse Farm and the social context of early Roman pottery production in Cambridgeshire. *Britannia 33*, 95–127.

Gill, D. W. J. (1988). Expressions of wealth: Greek art and society. *Antiquity 62*, 735–743.

Gill, D. W. J. (1991). Pots and trade: Spacefillers or objets d'art? *The Journal of Hellenic Studies 111*, 29–47.

Glaeser, E. L., M. E. Kahn, and J. Rappaport (2008). Why do the poor live in cities? The role of public transportation. *Journal of Urban Economics 63*, 1–24.

Glaeser, E. L., M. Resseger, and K. Tobio (2009). Inequality in cities. *Journal of Regional Science 49*, 617–646.

Greene, K. (1992). *Roman Pottery*. University of California Press.

Greene, K. (2005). Roman pottery: Models, proxies and economic interpretation. *Journal of Roman Archaeology 18*, 34–56.

Halstead, P. (1987). Traditional and ancient rural economy in Mediterranean Europe: Plus ça change? *Journal of Hellenistic Studies 107*, 77–87.

Hodder, I. (1974a). Regression analysis of some trade and marketing patterns. *World Archaeology 6*, 172–189.

Hodder, I. (1974b). Some marketing models for Romano-British coarse pottery. *Britannia 5*, 340–359.

Hodder, I. and M. Millett (1980). Romano-British villas and towns: A systematic analysis. *World Archaeology 12*, 69–76.

Izdebski, A., T. Słoczyński, A. Bonnier, G. Koloch, and K. Kouli (2020). Landscape change and trade in Ancient Greece: Evidence from pollen data. Economic Journal (forthcoming).

Johnston, A., A. Quercia, A. Tsaravopoulos, A. Bevan, and J. Conolly (2012). Pots, piracy and Aegila: Hellenistic ceramics from an intensive survey of Antikythera, Greece. *The Annual of the British School at Athens 107*, 247–272.

Kron, G. (2012). Standards of Living, Wealth. In *The Encyclopedia of Ancient History*. Wiley Online Library.

Lee, S. and J. Lin (2017). Natural amenities, neighbourhood dynamics, and persistence in the spatial distribution of income. *The Review of Economic Studies 85*, 663–694.

LeRoy, S. F. and J. Sonstelie (1983). Paradise lost and regained: Transportation innovation, income, and residential location. *Journal of Urban Economics 13*, 67 – 89.

Mieszkowski, P. and E. S. Mills (1993). The causes of metropolitan suburbanization. *Journal of Economic Perspectives 7*, 135–147.

Morris, I. (2007). Early Iron Age Greece. In W. Scheidel, I. Morris, and R. P. Saller (Eds.), *The Cambridge Economic History of the Greco-Roman World*, pp. 211–241. Cambridge University Press.

Osborne, R. (2007). Archaic Greece. In W. Scheidel, I. Morris, and R. P. Saller (Eds.), *The Cambridge Economic History of the Greco-Roman World*, pp. 277–301. Cambridge University Press.

Palmisano, A., A. Bevan, and S. Shennan (2017). Comparing archaeological proxies for long-term population patterns: An example from central Italy. *Journal of Archaeological Science 87*, 59 – 72.

Pliny the Elder (1991). *The Natural History: A Selection*. Penguin.

Rihll, T. and A. Wilson (1987). Spatial interaction and structural models in historical analysis: Some possibilities and an example. *Histoire & Mesure II*, 5–32.

Rosenthal-Heginbottom, R. (1995). Imported Hellenistic and Roman pottery. In *Excavations at Dor, Final Report IB: Areas A and C, Chapter 5*, pp. 183–288. Qedem reports, 2.

Smith, V. L. (1975). The primitive hunter culture, Pleistocene extinction, and the rise of agriculture. *Journal of Political Economy 83*, 727–755.

Sparkes, B. A. (2013). *The Red and the Black: Studies in Greek Pottery*. Routledge.

Tsingarida, A. (2013). Introduction: The markets of fine ware. In A. Tsingarida and D. Viviers (Eds.), *Pottery Markets in the Ancient Greek World (8th-1st Centuries B.C.):*

*Proceedings of the International Symposium held at the Universite Libre de Bruxelles 19-21 June 2008*. CReA-Patrimoine.

Veal, R. J. (2012). From context to economy: Charcoal as an archaeological interpretative tool. A case study from Pompeii, 3rd c. B.C. to A.D. 79. In I. E. Schrüfer-Kolb (Ed.), *More Than Just Numbers? The Role Of Science In Roman Archaeology*, pp. 19–52. Portsmouth, Rhode Island: Journal of Roman Archaeology Supplementary Series 91.

Vickers, M. and D. W. J. Gill (1994). *Artful Crafts: Ancient Greek Silverware and Pottery*. Clarendon Press.

von Reden, S. (2007). Classical Greece: Consumption. In W. Scheidel, I. Morris, and R. P. Saller (Eds.), *The Cambridge Economic History of the Greco-Roman World*, pp. 385–406. Cambridge University Press.

Williams, D. (2013). Greek potters and painters: Marketing and movement. In A. Tsingarida and D. Viviers (Eds.), *Pottery Markets in the Ancient Greek World (8th-1st Centuries B.C.): Proceedings of the International Symposium held at the Universite Libre de Bruxelles 19-21 June 2008*. CReA-Patrimoine.

Xenophon (1998). *The Economist*. Gutenberg EBook.

## Tables and figures

Table 1: Pottery summary statistics

| | Pottery piece counts for pottery quality | | | | | |
|---|---|---|---|---|---|---|
| | Minoan | | Hellenistic | | Late Roman | |
| | Raw | Weighted | Raw | Weighted | Raw | Weighted |
| Coarse | 5497 | 5342.85 | 32 | 16.10 | 49 | 19.50 |
| Medium | 906 | 833 | 818 | 433.66 | 1173 | 882 |
| Fine | 226 | 192.60 | 856 | 506.55 | 1369 | 1029.30 |
| Total | 6629 | 6368.45 | 1706 | 956.31 | 2591 | 1930.80 |

| Number of cells with at least one pottery piece by grade | | | | |
|---|---|---|---|---|
| | Minoan | Hellenistic | | Late Roman |
| | | Grid Cell Size | | |
| | | $633m^2$ | $70m^2$ | |
| Coarse | 541 | 29 | 22 | 42 |
| Medium | 364 | 172 | 377 | 704 |
| Fine | 108 | 243 | 399 | 835 |
| Number of cells with at least one pottery piece by grade | | | | |
| | 684 | 309 | 566 | 1310 |

| | Pottery piece counts for pottery thickness | | | | | |
|---|---|---|---|---|---|---|
| | Minoan | | Hellenistic | | Late Roman | |
| | Raw | Weighted | Raw | Weighted | Raw | Weighted |
| Thick | 516 | 491.40 | 101 | 60.10 | 102 | 69.90 |
| Non-Thick | 6113 | 5877.05 | 1605 | 896.21 | 2489 | 1860.90 |
| Total | 6629 | 6368.45 | 1706 | 956.31 | 2591 | 1930.80 |

| Number of cells with at least one pottery piece by grade | | | | |
|---|---|---|---|---|
| | Minoan | Hellenistic | | Late Roman |
| | | Grid Cell Size | | |
| | | $633m^2$ | $70m^2$ | |
| Thick | 225 | 83 | 75 | 91 |
| Non-Thick | 800 | 330 | 598 | 1442 |
| Number of cells with at least one pottery piece by grade | | | | |
| | 684 | 309 | 566 | 1310 |

Table 2: Correlation between type of consumption and total consumption

| | Minoan | Hellenistic | Late Roman |
|---|---|---|---|
| $corr(\log(1+p^{\mathscr{E}}_{\mathcal{C},c}), \log(P^{\mathscr{E}}_{\mathcal{C}}))$ | 0.97 | 0.14 | 0.06 |
| $corr(\log(1+p^{\mathscr{E}}_{\mathcal{C},m}), \log(P^{\mathscr{E}}_{\mathcal{C}}))$ | 0.70 | 0.75 | 0.63 |
| $corr(\log(1+p^{\mathscr{E}}_{\mathcal{C},f}), \log(P^{\mathscr{E}}_{\mathcal{C}}))$ | 0.57 | 0.69 | 0.63 |
| | Minoan | Hellenistic | Late Roman |
| $corr(\log(1+p^{\mathscr{E}}_{\mathcal{C},t}), \log(P^{\mathscr{E}}_{\mathcal{C}}))$ | 0.64 | 0.13 | 0.24 |
| $corr(\log(1+p^{\mathscr{E}}_{\mathcal{C},nt}), \log(P^{\mathscr{E}}_{\mathcal{C}}))$ | 0.98 | 0.96 | 0.96 |

Figure 1: The Mediterranean (original image courtesy of NASA Terra-MODIS)

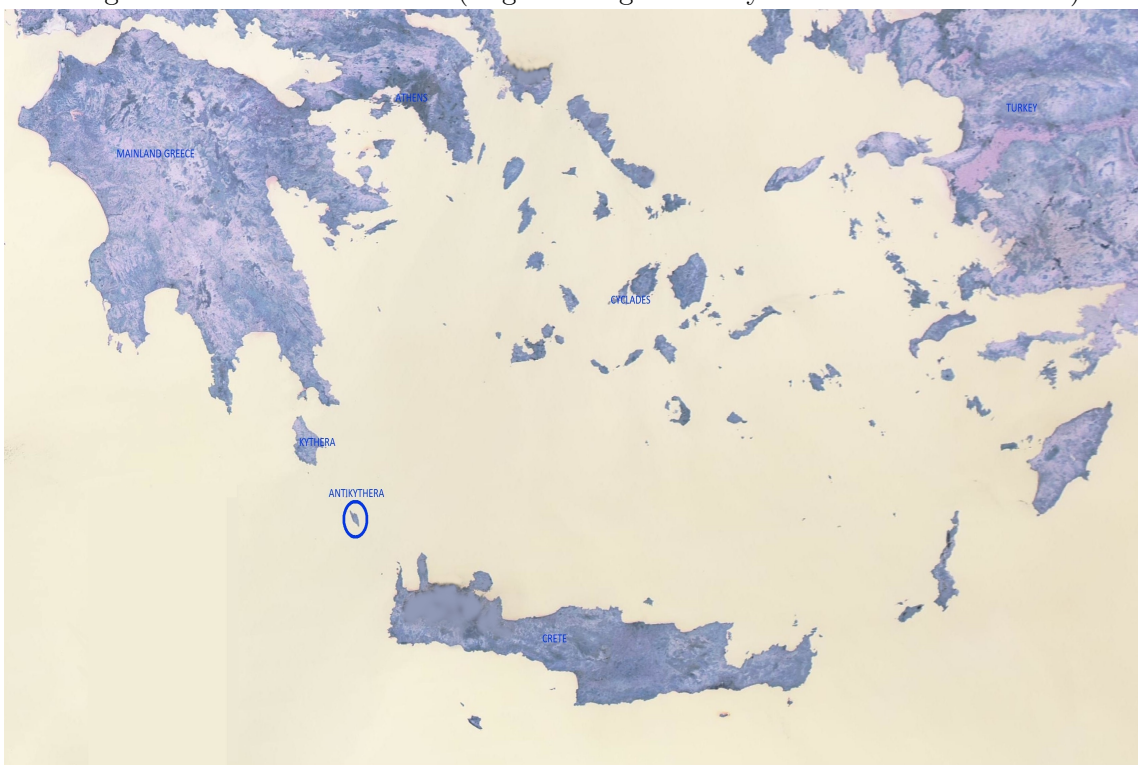

Figure 2: Antikythera

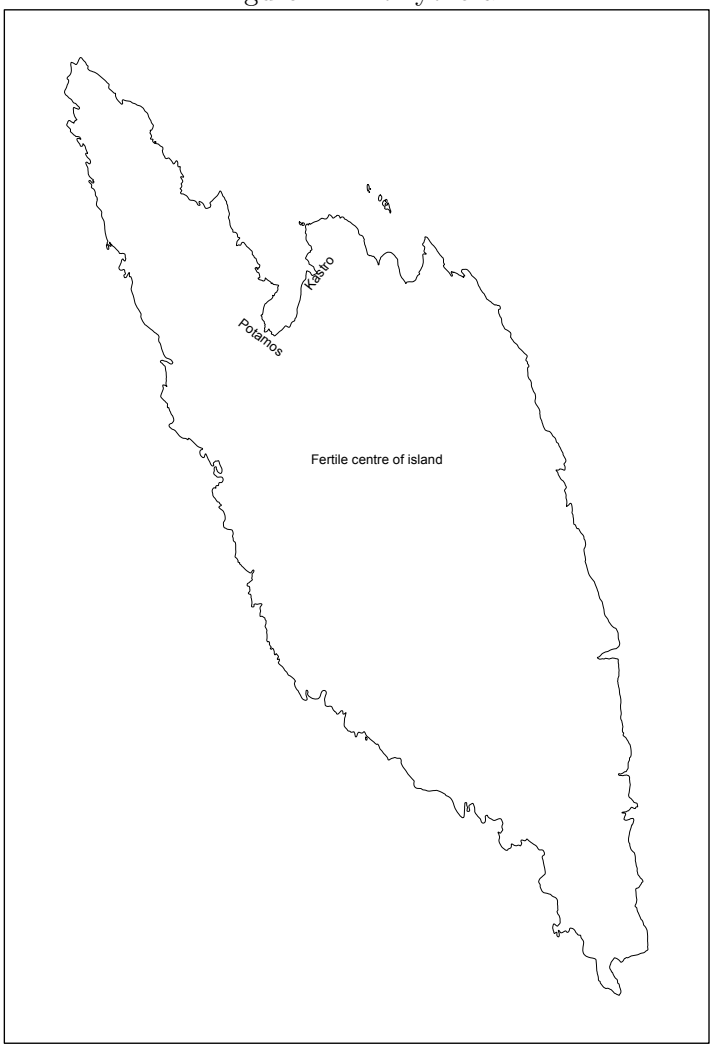

Figure 3: Coarse pottery locations: Minoan, Hellenistic, Late Roman eras (left to right)

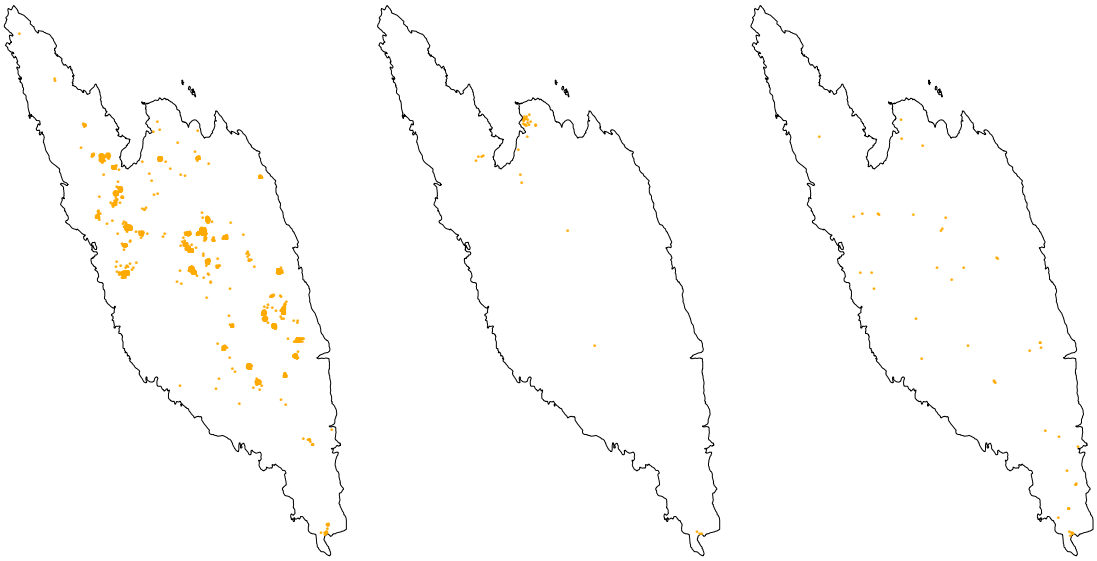

Figure 4: Medium pottery locations: Minoan, Hellenistic, Late Roman eras (left to right)

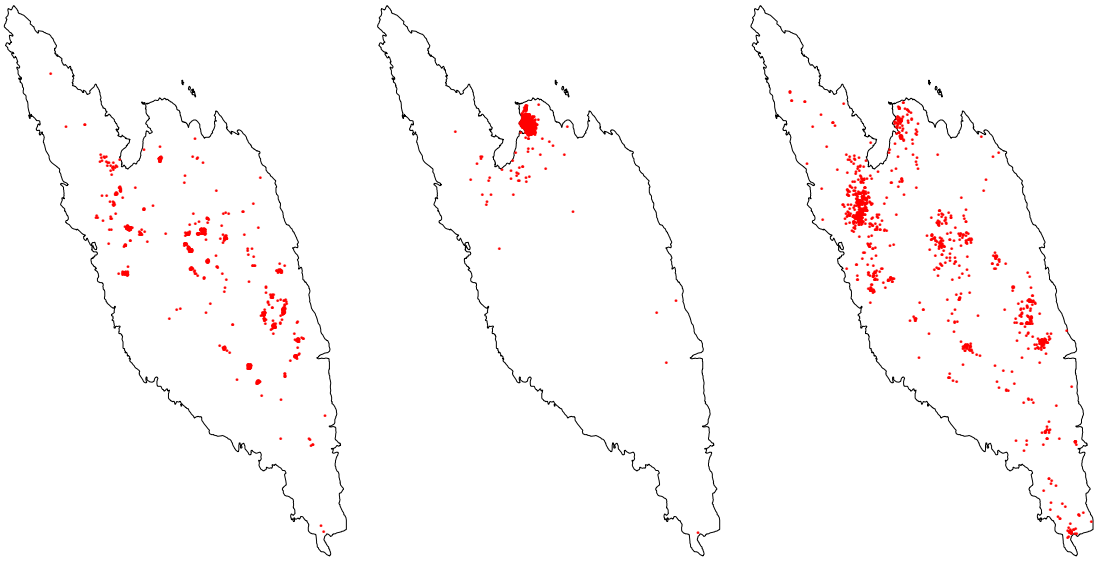

Figure 5: Fine pottery locations: Minoan, Hellenistic, Late Roman eras (left to right)

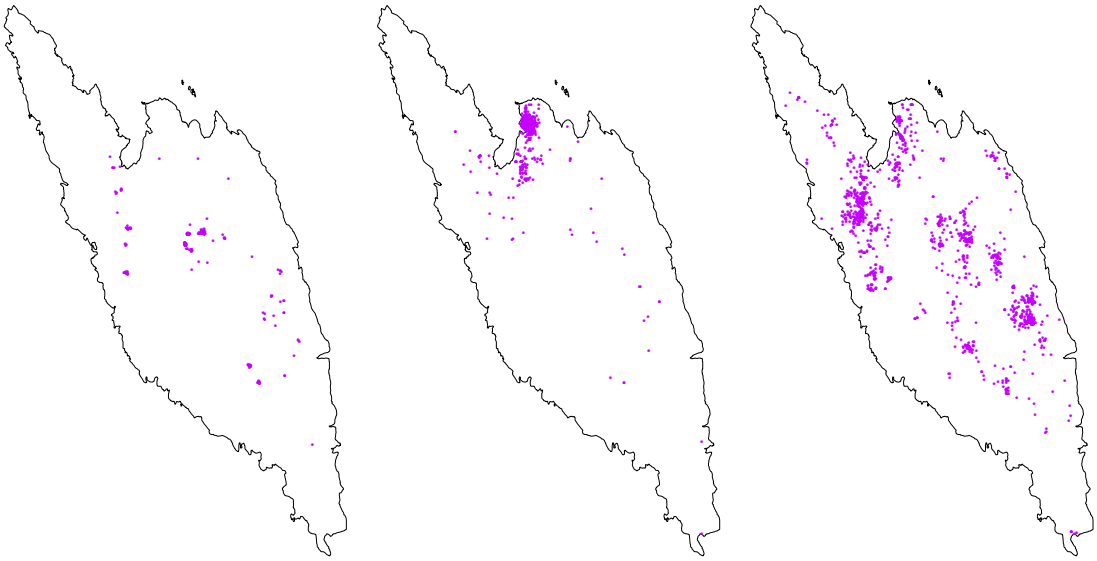

Figure 6: Thick pottery locations: Minoan, Hellenistic, Late Roman eras (left to right)

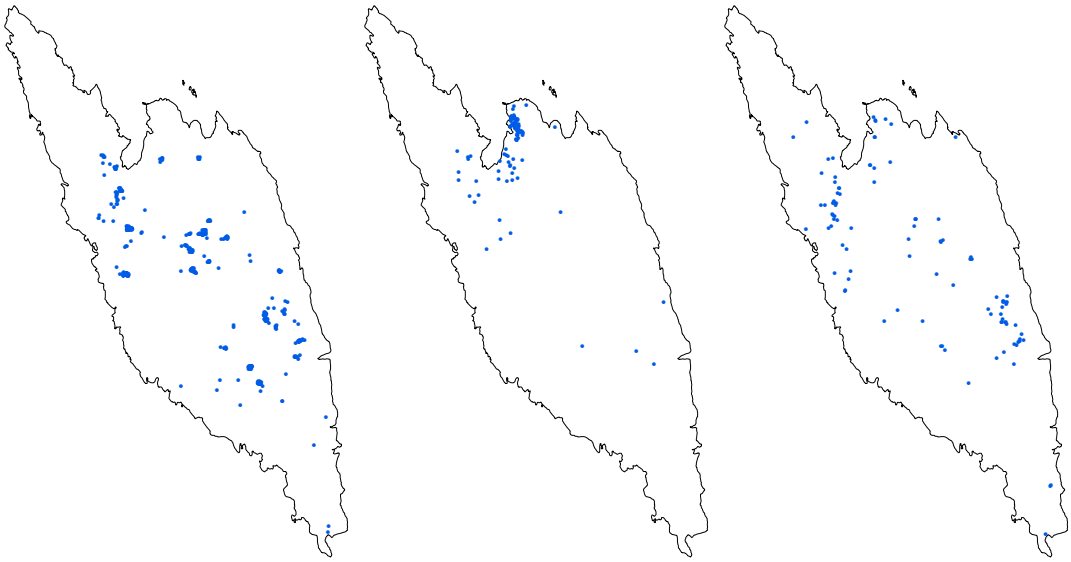

Figure 7: Non-Thick pottery locations: Minoan, Hellenistic, Late Roman eras (left to right)

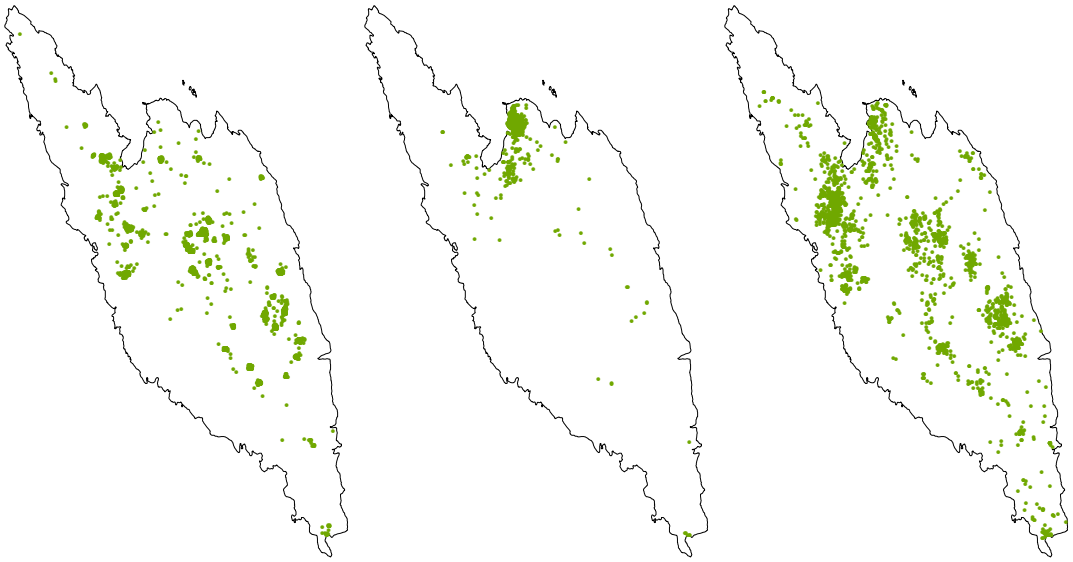

Figure 8: Density of raw counts: Minoan era

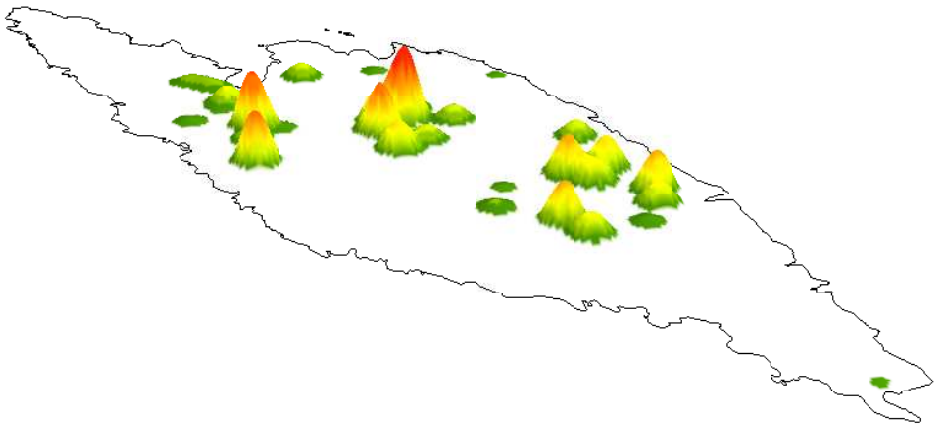

Figure 9: Density of raw counts: Hellenistic era

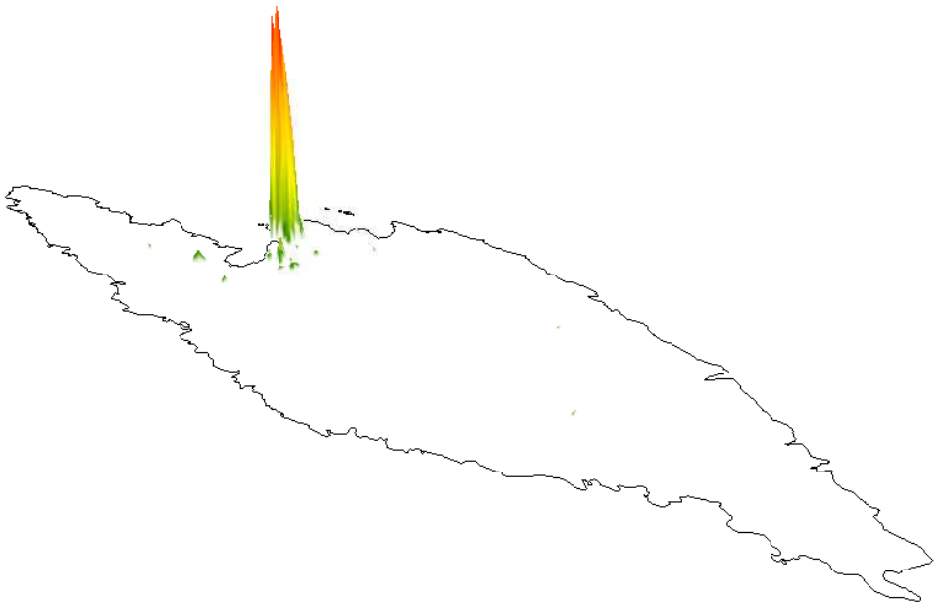

Figure 10: Density of raw counts: Late Roman era

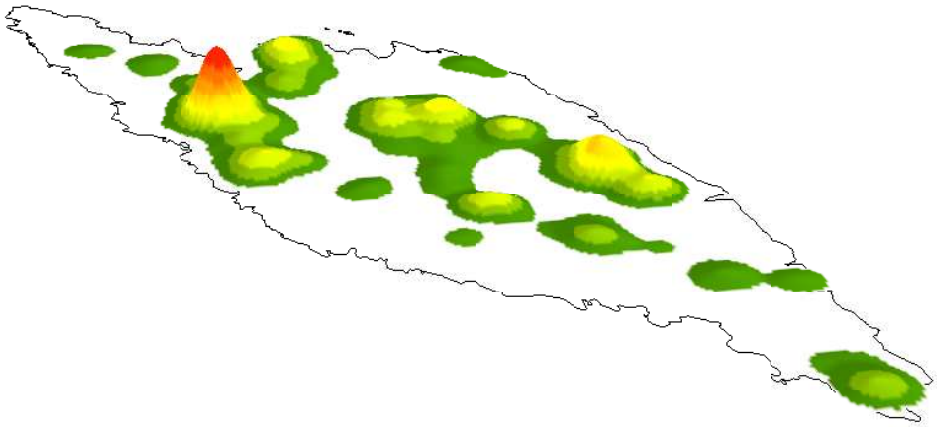

Figure 11: Nonparametric absolute consumption profiles by era: Minoan (top), Hellenistic (middle), Late Roman relative to fertile center (bottom left), Late Roman relative to Potamos (bottom right)

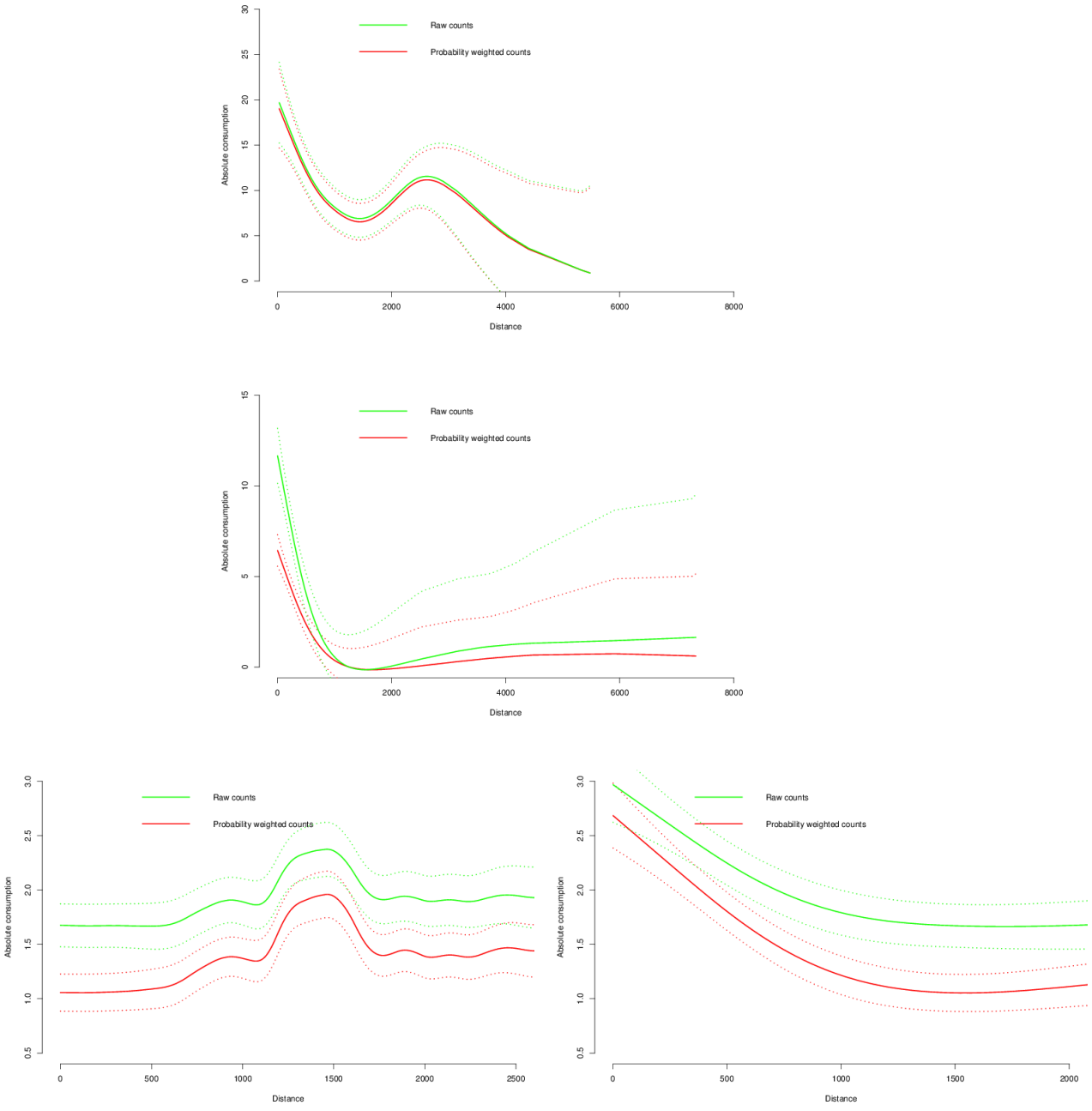

Figure 12: Relative consumption profiles: Hellenistic era

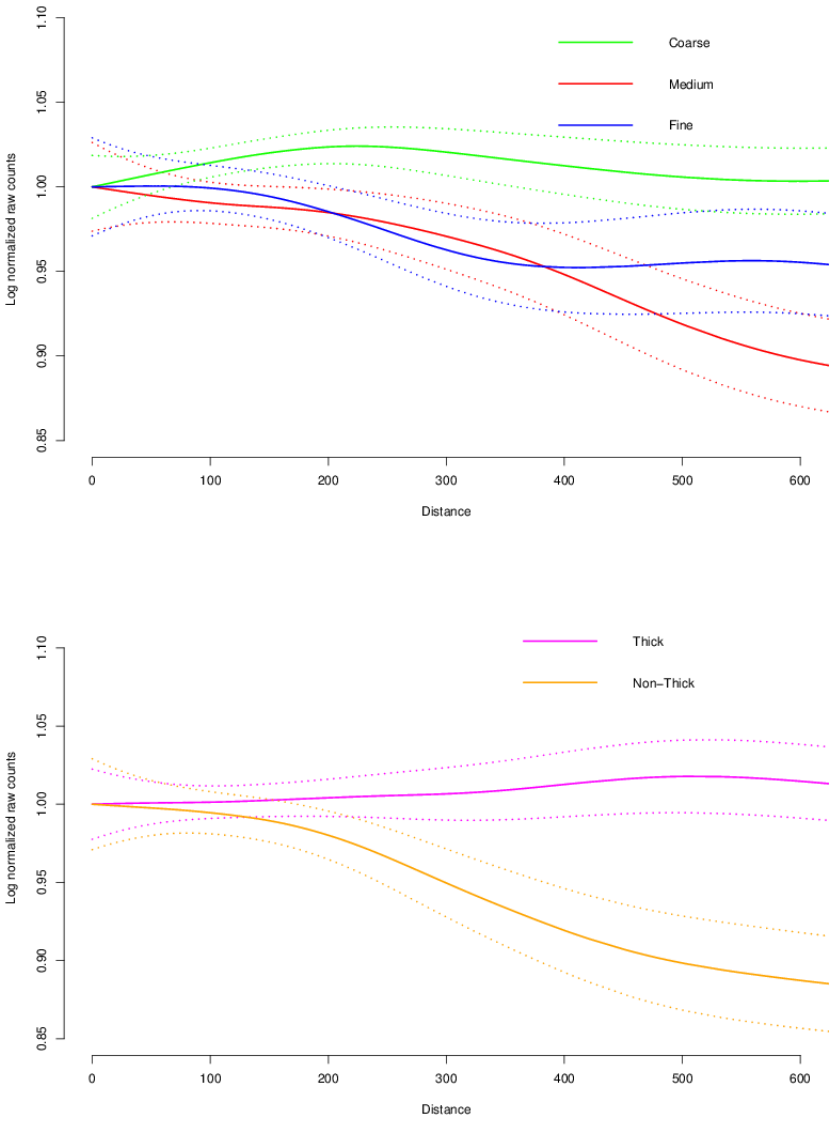

Figure 13: Relative (to Potamos) consumption profiles: Late Roman era

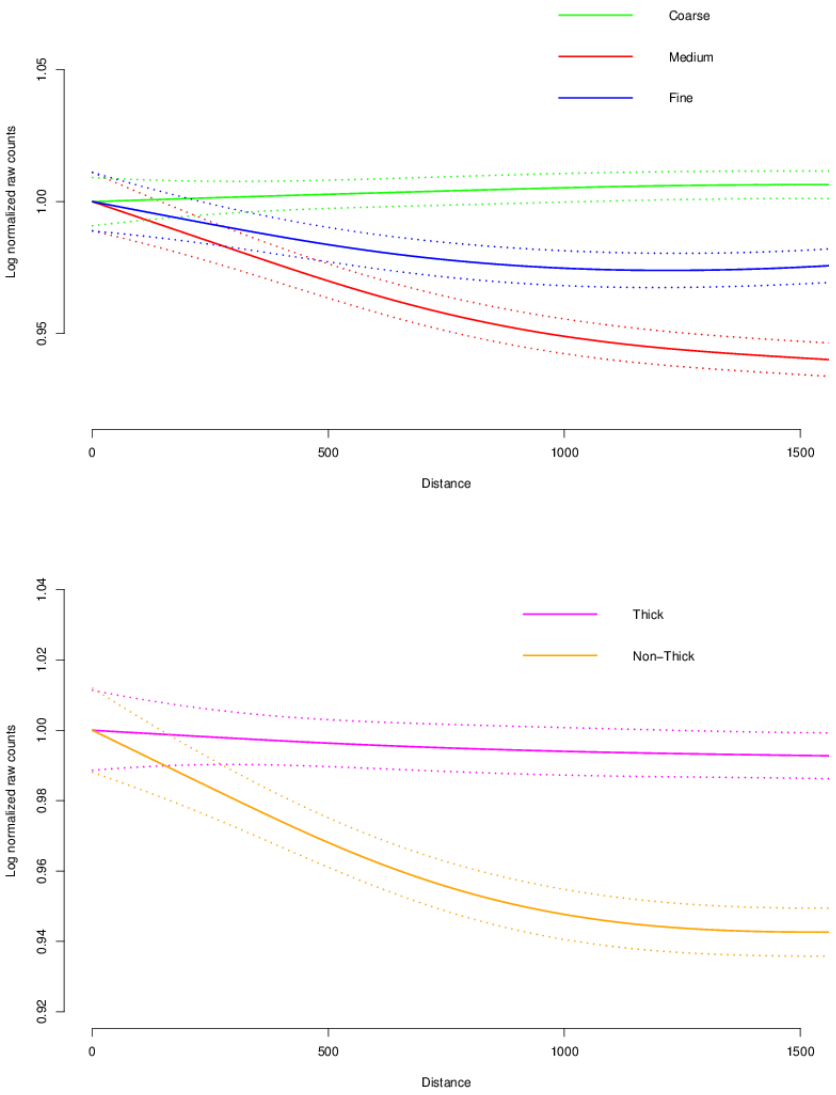

Figure 14: Relative (to fertile center) consumption profiles: Late Roman era

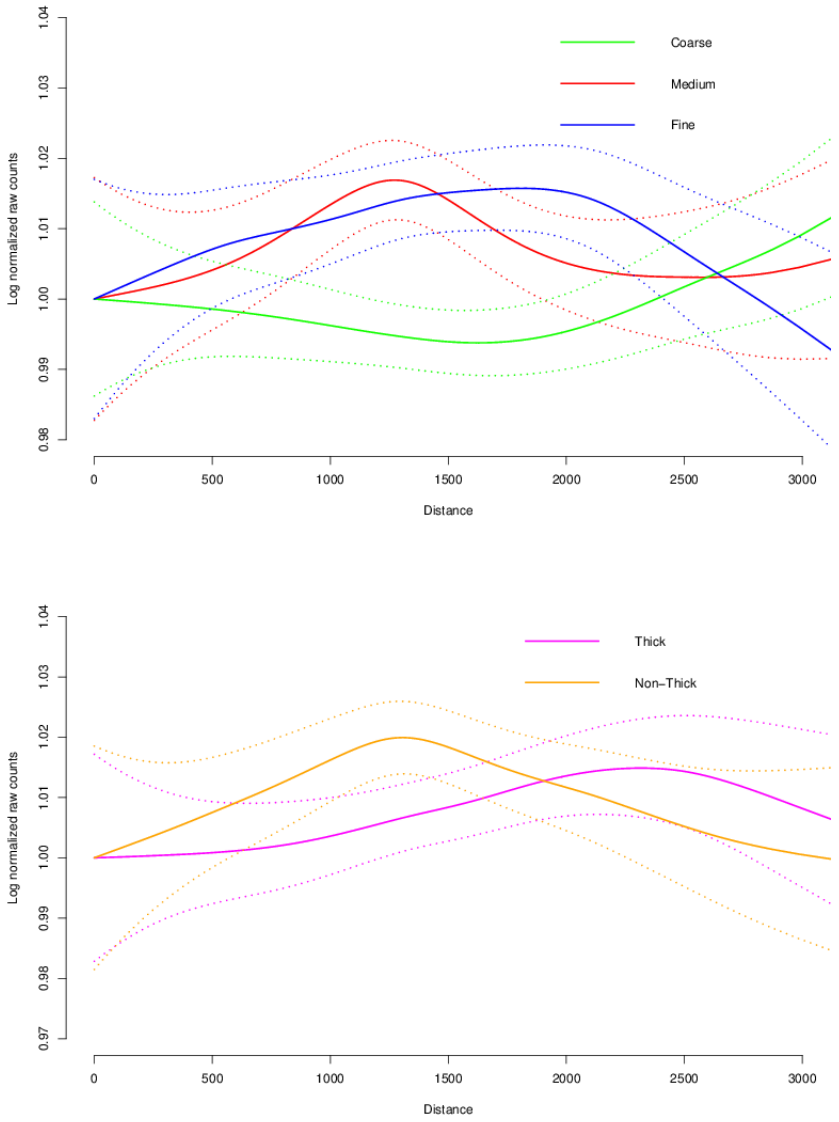

Figure 15: Relative consumption profiles: Minoan era

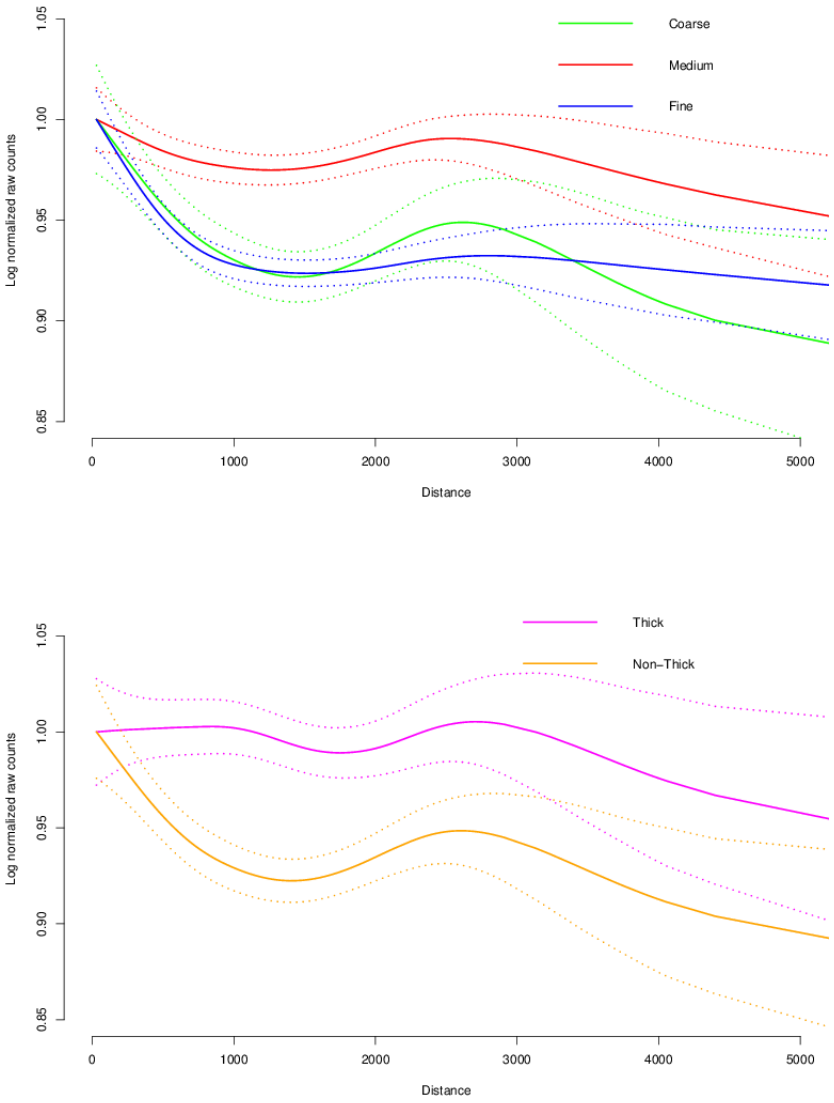

Figure 16: Relative consumption profiles excluding amphorae: Hellenistic era

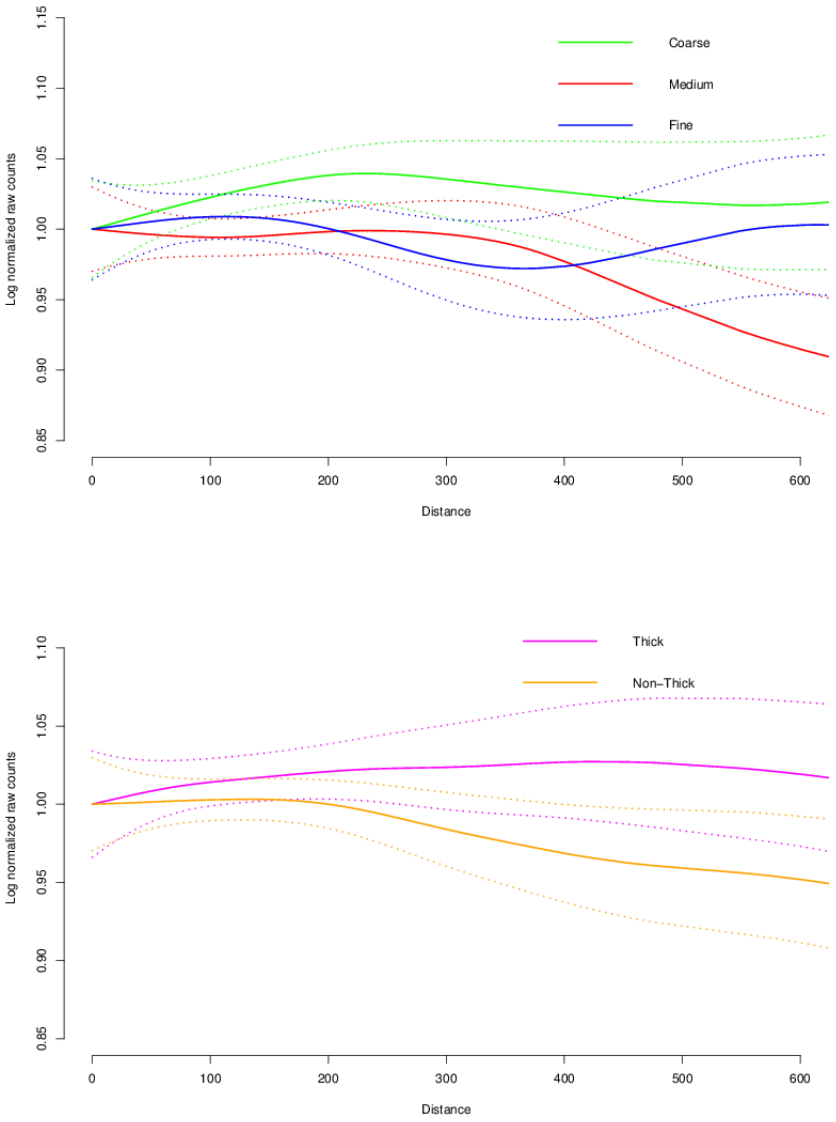

Figure 17: Relative (to Potamos) consumption profiles excluding amphorae: Late Roman era

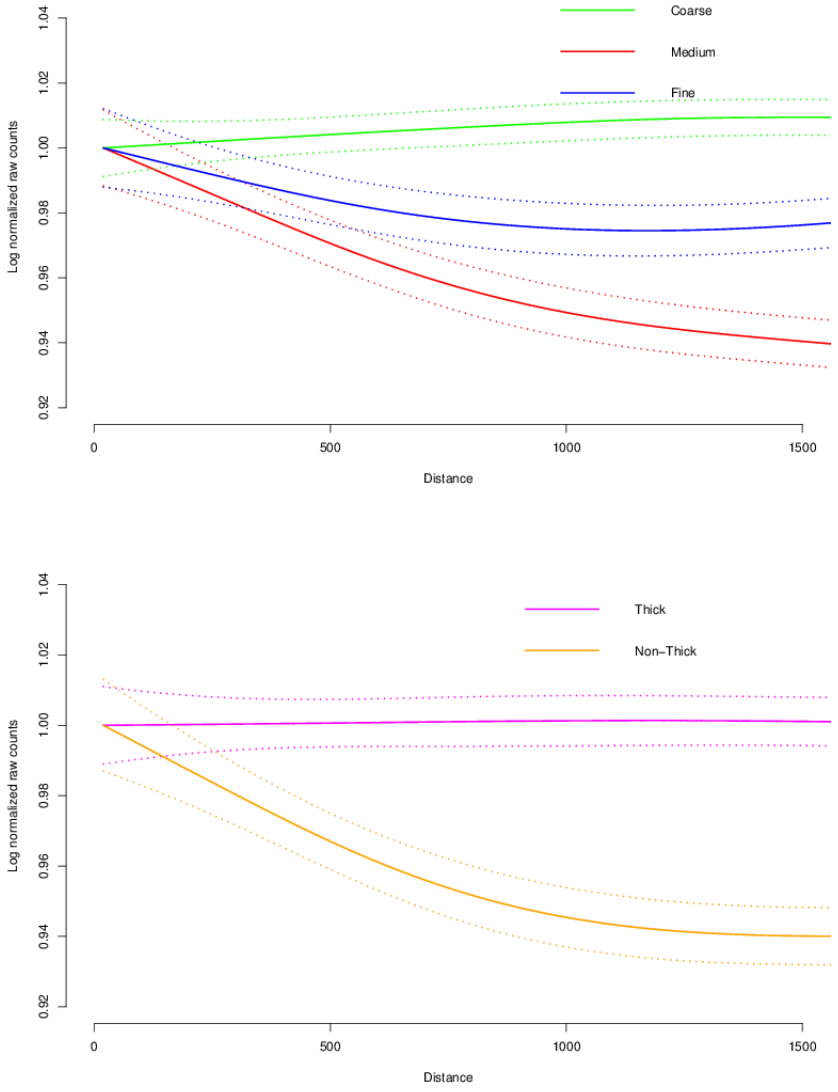

Figure 18: Relative (to fertile center) consumption profiles excluding amphorae: Late Roman era