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Unravelling the threads of connectivity: A mutual information approach to tracing material networks in the late Hellenistic and early Roman Mediterranean

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ABSTRACT

The study of connectivity and interaction in the Mediterranean world is a rich and vibrant topic. While most direct attestations of past interaction have been lost, we can use the ubiquity of material markers such as ceramic tablewares to trace the structures and underlying drivers of past networks. In this paper, we use an innovative combination of least cost path analysis and mutual information to explore the relative contributions of geographical proximity and potential social, economic, and political factors underlying the distributions of material culture. We apply this method to a case study using the ICRATES dataset of tablewares from the eastern Mediterranean in late Hellenistic and early Roman times (150 BCE – 50 CE). By exploring the multifaceted factors shaping these distributions, we enrich our understanding of ancient economies and trade networks, as well as provide further insight into broader questions of (cultural) exchange and power dynamics in the ancient world. Through this novel approach, we hope to pave the way for future research endeavours that seek to unravel the intricate threads of connectivity shaping past and present human societies.

1. Introduction

The Hellenistic world emerging from the conquests of Alexander did not consist of a single empire, but of a large interdependent network of kingdoms, dynasties, cities, associations, and people spanning the Mediterranean, Black Sea, Near East, and Western Asia. Joe Manning (2018, p. 40) identified four major factors that changed the face of the Mediterranean during the Hellenistic age (323-25 BCE): (1) migration; (2) imperial expansion; (3) long-distance trade; and (4) interstate competition. The common denominator across these factors was the intensification of (political and economic) connectivity and (social and cultural) interaction networks across the Hellenistic world. From the late third and early second centuries BCE onwards, a new player started to participate in these networks as the Romans became increasingly embroiled in the eastern Mediterranean (Alcock, 2010; Chaniotis, 2018). The Greek historian Polybius used the term *symploke* ('stitching together') to describe the interdependence of the western and eastern Mediterranean (Polyb. *Hist.* I.3.I-4) and the increasingly dominant role of Rome, culminating in the transformation of the Mediterranean into the *Mare Nostrum* ('Our Sea').

This paper seeks to develop an innovative approach to explore material culture as markers of connectivity and interaction by leveraging the complementary strengths of least cost path analysis and mutual information. Least cost path analysis provides crucial insights into the baseline geographical pathways of trade and exchange that can be compared with mutual information analysis to explore how material distributions deviate from this expected baseline. Through the integration and comparison of these two analytical approaches, we can distinguish between the relative contributions of geographical proximity and potential social, economic, and political factors that underlie the distributions of material culture. We will apply this method to explore the interplay between spatial proximity and socio-political dynamics in shaping the distribution patterns of tablewares across the eastern Mediterranean in late Hellenistic and early Roman times (150 BCE – 50 CE). One question to be considered in particular is how the rise of Rome in the eastern Mediterranean shaped and transformed existing patterns of connectivity and interaction.

The study of networks and connectivity aimed at uncovering the rich

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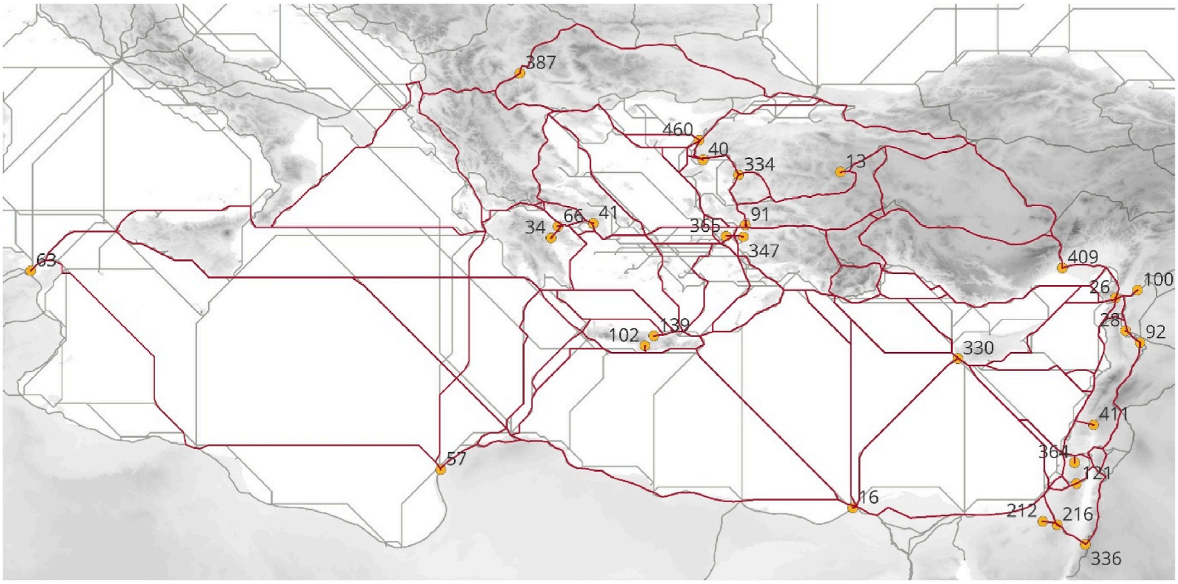

Fig. 1. Map with sites (yellow) and routes included in this paper. Routes in grey indicate unused routes and those in red indicate the shortest routes between sites across the Orbis network used as the basis for analysis (made by the authors). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

tapestry of complex interactions and exchanges that shaped ancient Mediterranean societies is a dynamic and multidisciplinary field that encompasses important contributions from archaeological, historical, and geographical perspectives (see amongst others: Abulafia, 2012; Broodbank, 2013; Hall and Osborne, 2022; Harris, 2005; Hodos, 2020; Horden and Purcell, 2000; López-Ruiz, 2022; Manning, 2018). Important topics explored in recent decades include.

(1) The identification of trade networks and economic exchange facilitating the spread of goods, ideas, and technologies (Brughmans and Poblome, 2016a; Carrignon et al., 2020, 2022; Charlesworth, 2016; McCormick, 2001).
(2) The production and distribution of material culture (Brughmans and Poblome, 2016b; Fenn and Römer-Strehl, 2013; Östborn and Gerding, 2015, 2016; Romanowska et al., 2021).
(3) Urban connectivity (Bes et al., 2020; Brughmans et al., 2012; Donnellan, 2019; Hanson, 2020; Kaiser, 2013; Raja and Sindbæk, 2020).
(4) Roads and maritime networks (Adams and Laurence, 2012; de Graauw et al., 2014; Leidwanger and Knappett, 2018; Manière et al., 2021; Marciak et al., 2023; McCormick et al., 2013; Meyer and Seland, 2023; Mills, 2018; Pažout et al., 2024; Tartaron, 2013).
(5) Socio-cultural exchanges and the spread of ideas, (religious) beliefs, and cultural practices (Collar, 2008, 2013; Glomb et al., 2020; Kaše et al., 2023; Kaše and Glomb, 2023; Mazzilli, 2022, 2023; Sweeney, 2016; Vela, 2019).

While much of the direct indicators of connectivity and interaction from the ancient world have been lost, we can use material culture as a proxy for some of the intricate interplay of human interactions, economic dynamics, and geopolitical landscapes. Ceramic tablewares hold a particularly relevant position as markers for the movement of people and goods due to their ubiquity in the archaeological record of the Mediterranean, as well as their relative narrow dating ranges allowing some degree of chronological fine-tuning. Yet, the usage of material culture as a proxy for past interaction is not without problems (Brughmans and Peeples, 2023, p. 156). These 'material residues' can only represent a fraction of the social, economic, and political dynamics of exchange in antiquity. Even in cases when production centres have been identified (and this is not always the case, see *infra*), pottery distribution patterns do not provide much detailed information regarding the nature and scope of movement from origins to find spot. All this does also not account for more peculiar customs such as, for example, related to re-use and recycling, as described by Herodotus in the case of collecting imported wine jars in Egypt and their repurposing as water jars in the Syrian desert (Herodotos III.6). Such customs will inevitably distort our picture of the distribution of material culture in ancient times.

The increasing popularity of network science in archaeology has resulted in a surge of exciting new studies in recent years, mainly relying on the tried and tested tools of social network analysis.(Brughmans and Peeples, 2023). This paper builds on this growing interest, but also takes a radically different approach through the combination of least cost pathways and mutual information as an alternative lens for the assessment of material culture distributions. The approach outlined here offers a novel methodological approach to help elucidating the myriad of multifaceted factors influencing connectivity and interaction in human societies. Through this study, we aim to not only enrich our understanding of ancient economies and trade networks, but also offer insights into broader questions of cultural exchange and power dynamics in the ancient world.

2. Materials and methods

2.1. Datasets

To trace the development of trade networks in the late Hellenistic and early Roman Mediterranean, we use a base network of maritime and land routes derived from the ORBIS geospatial network model (Scheidel, 2015).[1] The model simulates travel costs for various types of travel across the Roman empire. The model consists of 632 sites – from

[1] https://orbis.stanford.edu/.

Table 1
Hellenistic time slice with attestations of the five selected wares for the 28 selected sites (with ICRATES ID's as displayed on the maps and in the matrices).

Site ID	Site name	ESA	ESB	ESC	ESD	ITS
100	Gindaros	63,66	0,00	0,01	0,81	0,00
102	Gortyn	8,00	0,00	0,50	0,51	0,00
121	Jerusalem	12,13	0,00	0,00	2,83	0,00
13	Aizanoi	0,00	0,00	0,00	0,00	0,00
139	Knossos	20,72	0,00	1,13	2,74	0,00
16	Alexandria	17,41	0,00	2,23	0,00	0,00
212	Nessana	69,98	0,00	0,00	1,62	0,00
216	Oboda	9,29	0,00	0,00	3,64	0,00
26	Antiocheia ad Orontem	31,84	0,00	0,00	0,40	0,00
28	Apamea	74,65	0,00	0,00	0,00	0,00
330	Paphos	92,58	0,00	0,79	21,88	0,00
334	Pergamon	0,00	0,00	5,63	0,00	0,00
336	Petra	47,56	0,00	0,00	0,40	0,00
34	Argos	9,05	0,00	1,07	0,00	0,00
347	Priene	0,58	0,00	0,00	0,00	0,00
364	Samaria-Sebaste	36,26	0,00	0,00	2,02	0,00
365	Samos	8,16	0,00	2,84	0,00	0,00
387	Stobi	5,92	0,00	2,59	0,00	0,00
40	Assos	3,47	0,00	89,03	0,00	0,00
409	Tarsos	51,76	0,00	0,00	0,40	0,00
41	Athens	51,22	0,00	1,34	0,00	0,00
411	Tel Anafa	120,94	0,00	1,45	1,83	0,00
460	Troia	1,74	0,00	2,58	0,00	0,00
57	Berenice (Libya)	15,53	0,00	0,00	1,32	0,00
63	Carthage	3,98	0,00	0,00	0,40	0,00
66	Corinth	5,03	0,00	0,00	0,00	0,00
91	Ephesos	29,70	0,00	4,74	0,00	0,00
92	Epiphaneia	149,67	0,00	0,00	1,62	0,00

Table 2
Roman time slice with attestations of the five selected wares for the 28 selected sites with ICRATES ID's as displayed on the maps and in the matrices).

Site ID	Site name	ESA	ESB	ESC	ESD	ITS
100	Gindaros	84,27	0,00	0,79	1,19	0,00
102	Gortyn	12,96	2,13	3,75	1,49	36,06
121	Jerusalem	62,77	3,00	0,84	7,06	11,91
13	Aizanoi	0,00	10,03	0,00	0,00	0,00
139	Knossos	52,77	23,56	7,41	8,76	57,41
16	Alexandria	26,16	4,53	3,90	1,71	18,93
212	Nessana	94,57	0,00	0,00	11,41	0,00
216	Oboda	29,77	1,00	0,00	28,06	10,47
26	Antiocheia ad Orontem	142,20	1,01	0,00	0,60	16,46
28	Apamea	150,27	0,00	0,00	0,00	4,12
330	Paphos	73,27	2,81	5,80	61,17	17,77
334	Pergamon	0,00	0,51	17,17	0,00	0,81
336	Petra	60,01	1,01	0,00	1,11	22,65
34	Argos	17,43	0,07	6,97	0,35	41,44
347	Priene	1,42	15,25	0,00	0,00	0,00
364	Samaria-Sebaste	59,36	0,04	0,00	4,83	4,08
365	Samos	23,86	2,16	6,91	0,00	1,36
387	Stobi	4,06	0,81	10,75	0,00	28,07
40	Assos	9,62	6,30	412,24	0,00	5,75
409	Tarsos	122,24	1,54	0,00	7,28	8,49
41	Athens	100,03	28,11	4,56	0,52	88,59
411	Tel Anafa	135,06	1,02	2,99	6,51	1,00
460	Troia	1,26	2,08	19,85	0,00	1,53
57	Berenice (Libya)	47,33	3,12	0,00	4,54	103,95
63	Carthage	8,44	0,00	0,00	0,60	100,47
66	Corinth	27,55	19,00	2,29	1,18	89,48
91	Ephesos	89,44	141,24	15,21	0,00	42,52
92	Epiphaneia	312,36	0,00	0,00	3,38	6,72

Eburacum in Britain to Singara in Mesopotamia – 1026 maritime routes, and more than 100,000 km of roads, tracks and navigable rivers. All connections between sites are assigned cost factors. Maritime travel is defined by a cost surface simulating monthly wind conditions, currents, and wave height. Road travel is restricted through costs based on topography, and fluvial travel is determined by river currents. Travel routes are calculated through Dijkstra distance (a least-cost algorithm, see *infra*) taking into account a cost value for travel such as monetary costs, time, or Euclidean distance, respectively representing the cheapest, fastest and shortest routes.

The sites included in the model broadly reflect historical conditions around 200 CE. However, here we use the dataset as the foundation for a more extensive analysis regarding the late Hellenistic and early Roman periods (150 BCE – 50 CE). We opted not to use the online interface of the model, but import the geospatial data into QGIS for further analysis.[2] While this reduces some of the pre-defined possibilities of the web-based interface, for example, the option of simulating up to fourteen different modes of road travel or simulating travel conditions at different times of the year, it facilitates the integration with other datasets and methods in the analytical pipeline (see *infra*).

The metaphorical blood moving through these arteries of ancient interaction is represented by proxy through distribution patterns of terra sigillata pottery during the late Hellenistic and early Roman periods. This data is derived from the *Inventory of Crafts and Trade in the Roman East (ICRATES)* dataset (Bes et al., 2019), including almost 34,000 sherds from 275 sites, predominantly from the Mediterranean East, dated to 200 BCE – 700 CE.[3]

Analysing and interpreting the full ICRATES dataset would go beyond the scope of the present paper. We therefore focused on the five most prevalent wares from 150 BCE to 50 CE: the four main Eastern Sigillata productions (ESA, ESB, ESC, and ESD) and Italian Terra Sigillata (ITS).[4] We then filtered 28 sites yielding high numbers for at least one of these wares as the core dataset for our analyses (Fig. 1). To assess chronological changes from the late Hellenistic into the early Roman period, we created two time slices of 100 years (150-50 BCE and 50 BCE-50 CE) (see Tables 1 and 2), using a time slicing pipeline established in previous work (Daems et al., 2023).

3. Methods

Least cost path (LCP) analysis has been established as a valuable tool in archaeological research, providing a spatially informed approach to understanding past human behaviours, movement patterns, and landscape utilization (Herzog, 2020). LCP is based on the principle of movement efficiency across pathways of least resistance (White and Surface-Evans, 2012). The primary objective is to identify routes between a given set of points that are least costly or require least effort given a certain cost factor (e.g. time or energy expenditure) (Conolly and Lake, 2006, p. 234). This cost factor is defined through a cost surface in which each cell of a raster dataset represents the cost of travelling to or across that location. Costs can be calculated by one or several factors such as terrain, slope, land cover, etc. which are assigned weights based on their expected (empirical or theoretic) impact on movement (Herzog, 2020, p. 335). The cumulative cost of all traversed cells determines the overall difficulty of any given route. LCP algorithms then calculate optimal pathways, minimizing total travel costs.

A major distinction in travel costs for the ancient world pertains to the difference between land and maritime travel. Based on sources such as the Price Edict of Diocletian (301 CE), scholars have been able to calculate that for the transport of 550 kilos of grain over a 100 mile land route, costs increased by 56 percent, whereas the transportation of the

[2] Network data obtained from: https://purl.stanford.edu/mn425tz9757; Accessed on 05/01/2024.

[3] https://archaeologydataservice.ac.uk/archives/view/icrates_lt_2018/; Accessed 05/01/2024.

[4] For an extensive discussion of the characteristics, origins, and chronology of these wares, see Bes (2015).

same freight from Alexandria to Rome (more than 1200 miles as the crow flies) over sea would incur only a 2 percent price increase (Meijer and Nijf, 1992, p. 133). To deal with this discrepancy, we used the weighted cost values calculated in the Orbis geospatial network that explicitly address this issue.[5] We then rasterized the geospatial vector data to calculate an overall least cost matrix with the "*Shortest path (point to layer)*" algorithm in QGIS.

LCP has proven instrumental in exploring ancient route networks (for an overview, see Verhagen et al., 2019). By considering factors like topography and natural barriers for land routes or sea currents and prevailing winds for maritime routes, researchers can model potential trade routes and identify lines of interaction conducive to (economic) exchange (Batten, 2007; Massa and Palmisano, 2018; Palmisano, 2018; Tsirogiannis and Tsirogiannis, 2016). However, several notes of criticism have been voiced regarding methodological issues and their implications for the results of LCP analysis when performed uncritically (Herzog, 2014; Lewis, 2023). It can, for example, be noted that several cost functions can be used, each potentially providing different outcomes. Optimising which cost function 'best' explains a given route is only rarely done, prompting calls for a more probabilistic approach to route network analysis incorporating a multiple-models approach (Lewis, 2023) and the explicit assessment of uncertainty in calculating LCP results (Lewis, 2021). Moreover, even though technically cost functions can be calculated for every type of factor, it remains difficult to find suitable proxies for factors beyond geography, such as social, cultural, political, and economic costs influencing patterns of mobility and interaction.

Here, we opted for a simple LCP analysis to function as a starting point for establishing a baseline of expected geographical 'ease' for the distribution of tableware, and then compare this with the results of a mutual information analysis to explore and interpret the role of other potential factors underlying this distribution. Mutual information (MI) is a fundamental concept in information theory that quantifies the amount of information shared between two variables, and thus assesses their mutual dependencies. More specifically, it measures the reduction in uncertainty about one variable when the value of the other variable is known (Cover and Thomas, 2006). MI has only started to be applied in archaeology in recent years, amongst others to trace patterns of cultural transmission in rock art (Caridi and Scheinsohn, 2016), as a way to remove uncorrelated features for archaeological ceramics classification by laser-induced breakdown spectroscopy (Ruan et al., 2021), as a similarity measure to train an algorithm for the registration of archaeological geophysical images (Karamitrou et al., 2017), and to calculate synchrony in energy consumption by past human societies (Freeman et al., 2018).

The red thread running through this diverse set of applications is the suitability of MI for the extraction of meaningful insights from complex data patterns. We therefore turned to MI to help untangle the complex web of interactions and connections that characterized the ancient world. We calculated MI for the selected sites based on the shared presence or absence of the five selected pottery wares. This means that low MI values represent an independent pattern of material assemblages, whereas high values represent dependent patterns, which implies reduction in uncertainty in interpreting the material assemblage of site A when we know the assemblage from site B.

4. Results

The LCP analyses provide a baseline to assess the comparative 'ease of transfer' for the flows of people and goods across the Mediterranean. In Fig. 2, we visualize these flows through a network in which the edges are represented by the inverse of the least cost path values between each pair of sites.[6]

We can observe a number of interconnected clusters each consisting of a set of nodes located within comparative close distance on the regional levels of mainland Greece, Asia Minor, the northern Levant, and southern Levant. Across these clusters, strong ties exist within the Aegean, consisting of mainland Greece, Crete, and Asia Minor, as well as between the northern and southern Levant. At the same time, weaker ties connect the Aegean with the Levant, Egypt (through Alexandria) and other areas of the Mediterranean. Unsurprisingly, more westward located sites such as Carthage and Berenice – as well as inland sites such as Aizanoi – are particularly weakly connected due to the large distances or difficult land routes needed to reach these sites. In the case of Carthage, the dominance of local/regional productions of terra sigillata such as African Red Slip Ware (ARSW) during the early Roman period can be highlighted as well.

The cost matrix in Fig. 3 provides a basis of comparison for the starting hypothesis that sites that are easily reachable from a production place will tend to display high frequencies of the material produced there, whereas sites with higher transportation costs will generally feature lower amounts of this material. Focusing specifically on the Eastern Sigillata productions, the origins of ESA, ESB, ESC, and ESD are placed for the purposes of this paper,[7] respectively, at Antioch,[8] Ephesos, Pergamon, and Paphos.[9]

To explore our starting hypothesis, we turn to the well-established framework of cultural transmission (Cavalli-Sforza and Feldman, 1981; O'Brien, 2008; Walsh et al., 2019) and postulate a set of choices and preferences for the consumption of material culture (Table 3) to compare the amounts of attested material with travel costs between the production site and the findspot. Conformist behaviour can be presumed in cases of low costs and high amounts of material, as well as with high costs and low amounts of material. Deviations of this economic rationality are observed in cases of low amounts of material at sites with low costs and with high amounts of material in cases of high cost, corresponding, respectively, to anti-conformist and intrinsic preference choices.

ESA is attested at every site in the dataset in both the Hellenistic and Roman time slices, except for Aizanoi (an inland site) and Pergamon (a known pottery production centre). For the presumed origins of ESA in or near Antioch, the sites with the lowest travel costs are Gindaros, Apamea, Epiphaneia, Tarsos, Tel Anafa, Paphos, Samaria, Jerusalem, Nessana, and Oboda. All are located in southeastern Turkey, Cyprus, and the Levant. Adhering to the norm of conformist choices, the highest amounts of ESA have been found at these sites. A handful of other sites with high amounts of ESA can be identified: Knossos, Petra, Alexandria, Athens, Berenice, and Ephesos. These can therefore be subsumed under the category of intrinsic preference for this product. The high amount of material found at Petra is particularly striking given the high cost of travel from Antioch. The role of caravan routes connecting the northern and southern Levantine areas could be suggested as particularly relevant here.

ESB has been attested in Roman times at every site barring Gindaros, Apamea, and Nessana. Of these, the former two are firmly within the

[5] See the Introduction on the Orbis web page for an explanation of the choices informing this calculation.

[6] Given that in LCP analysis, low values represent low costs of movement, we opted to invert the values so that thicker lines represent easy access routes.

[7] Given our focus on a large-scale perspective encompassing the Mediterranean East, we had to make choices regarding the placement of these points of origin which do not necessarily reflect the full nuance of the current scholarly debate (see following footnotes).

[8] The exact production center of ESA has not been conclusively identified, but current scholarship suggests the area between Tarsus in southeast Turkey and Latakia in Syria, with Antioch as a likely candidate (see Bes, 2015 for a more extensive discussion).

[9] While some have argued for a Levantine origin such as Oboda, most scholars have settled on Cyprus or perhaps southwestern Anatolia as the most likely production area. We choose Paphos as a general stand-in for the island.

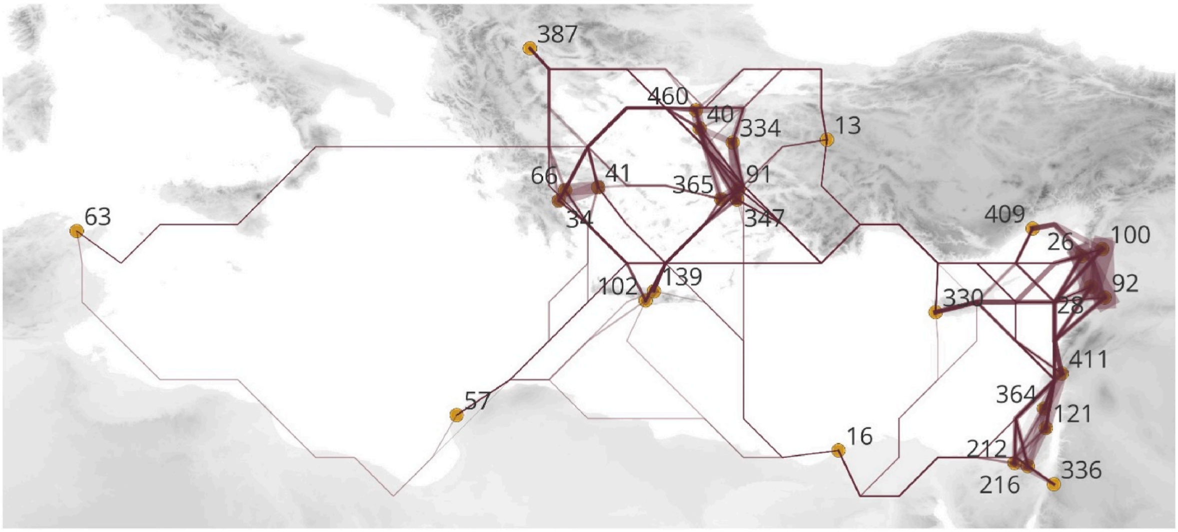

Fig. 2. Weighted network of inverted least cost path values, where the thickness of the line corresponds to easiness of travel (made by authors).

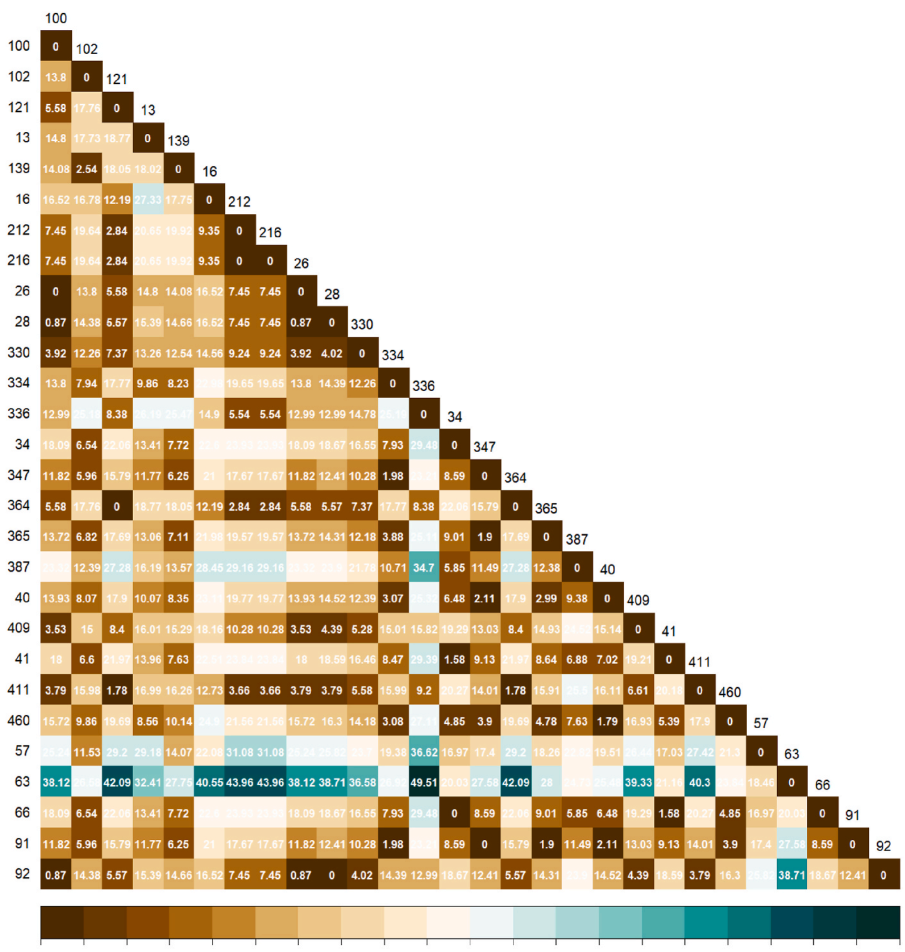

Fig. 3. Cost matrix for the connections between all 28 sites (made by authors).

influence zone of Antioch and display a strong preference towards ESA. The presence of ESB at other sites in the region – Gindaros, Epiphaneia, and Antioch itself – is also negligible. For Ephesos, sites with low travel costs are the other sites from Asia Minor: Priene, Pergamon, Assos, Troia; as well as the island of Samos, Knossos on Crete, and Argos, Corinth, and Athens in Greece. Of these, only Troia and Pergamon have none or very low amounts of ESB, which could be linked to anti-conformist choices. For Pergamon, the explanation can perhaps be found in a strong preference for its own production of ESC as hardly any other terra sigillata product is attested at the site. Likewise for Troia, ESA, ESB, and ITS have been attested only in low numbers, whereas ESC is attested abundantly. Assos was located most closely to Troia and

Table 3
Consumer choice matrix for material culture.

	Low cost	High cost
Low amounts of material	Anti-conformist	Conformist
High amounts of material	Conformist	Intrinsic preference

yielded every type of terra sigillata, except ESD (following a broader regional trend), but yielded extraordinary amounts of ESC (the highest amount of all sites in our dataset). Clearly, this site can be situated firmly within the dominant zone of influence of ESA. For the sites outside of the low cost zone of Ephesos, we can highlight Aizanoi, the only site in our dataset located at a considerable distance from the Mediterranean coast in the interior of Anatolia. ESB is the only sigillata ware attested at this site, indicating that travel costs towards the interior were too high for high amounts of materials to reach the city. Yet, the clear preference for ESB rather than the Pergamene ESC is remarkable given that the cost is slightly higher for the former.

ESC and ESD have comparatively smaller distribution networks compared to ESA and ESB, with the former attested at only 16 out of 28 sites and the latter at 19. The sites with relative low travel costs from Pergamon are Priene, Ephesos, Troia, Samos, Athens, Corinth, Argos, Knossos, Gortyn, and Aizanoi. Of these, Aizanoi and Priene yield no ESC as both display a strong preference towards ESB. For Paphos on Cyprus, sites within the low cost zone are Gindaros, Antioch, Apamea, Tel Anafa, Jerusalem, Samaria, Tarsos, and Epiphaneia. Of these, Gindaros, Antioch, and Apamea have hardly any ESD. Instead, these three sites all explicitly favour ESA. At the same time, even though the other sites of Jerusalem, Epiphaneia, Samaria, Tarsos, Berenice, and Tel Anafa have modest numbers of ESD, their main preference likewise lies with ESA. Interestingly, outside of Paphos itself, the highest amounts of ESD have been attested at Oboda and Nessana, which are located slightly outside of the low cost zone of Paphos. Whereas for Nessana the main preference lies again with ESA, at Oboda ESA and ESD occur in almost the same numbers.

Finally, we grouped all of the Italian terra sigillata (ITS) productions together to explore the distribution of this material throughout the eastern Mediterranean. Unsurprisingly, Carthage and Berenice as the most westward points in our dataset have the highest numbers of ITS. Other sites where this ware is attested extensively are Gortyn and Knossos on Crete, Athens, Corinth, Argos, and Stobi in Greece, Ephesos in Asia Minor, Alexandria in Egypt, Paphos on Cyprus, and Antioch and Petra in the Levant. It must be noted that its widespread attestation is likely at least in part a result of recognition/publication bias as ITS is easily recognizable and its good quality, shiny slips, fine decoration, and stamps all favour extensive publication focus. Even so, given the wide spread of this ware throughout the Mediterranean, its almost complete absence at sites such as Apamea, Pergamon, Troia, Samos, and Priene is remarkable and could be a sign of anti-conformist choices and clear preferences for other, regional products.

Having established this baseline, we can now cross-compare the cost matrix with the MI analysis. In Figs. 4 and 5, we show matrices in which we divide MI values by the cost values for, respectively, the Hellenistic and Roman period. High values represent connections between sites with high MI and low costs. On the flip side, low values will almost always be generated for sites with high cost values, regardless whether

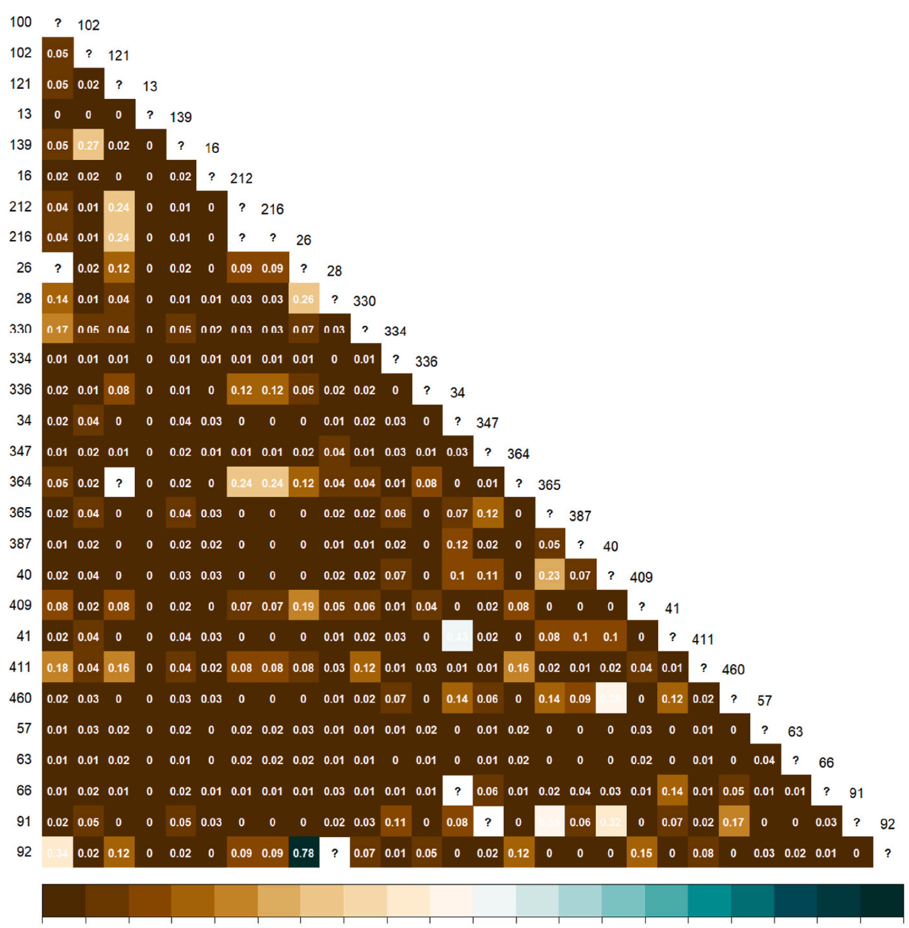

Fig. 4. Matrix with MI values over cost values for the Hellenistic period. Question marks indicate instances where cost is zero (for very closely located sites) and therefore the value of the MI-LCP ratio is undefined. (made by authors).

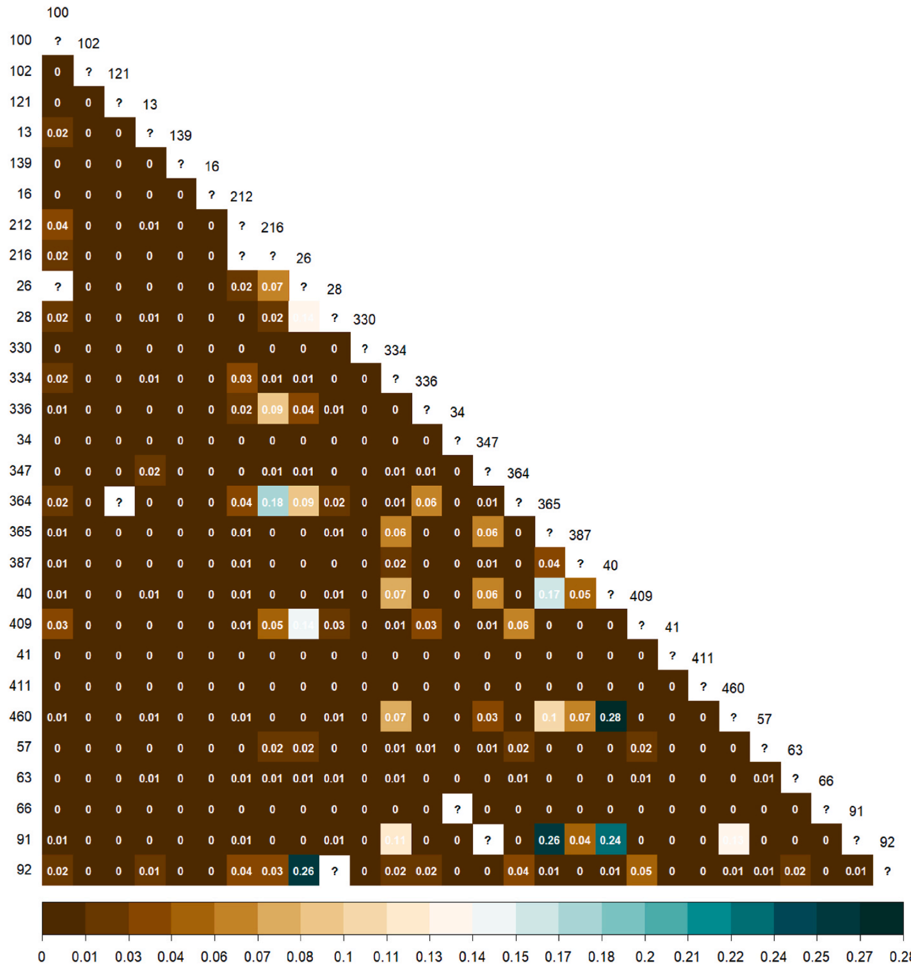

Fig. 5. Matrix with MI values over cost values for the Roman period. Question marks indicate instances where cost is zero (for very closely located sites) and therefore the value of the MI-LCP ratio is undefined (made by authors).

pairwise MI is high or low. These figures are therefore mostly relevant to explore the low cost value connections.

For the Hellenistic period, we see a variable picture with a wide range of values, but generally following expected patterns in regional clusters showing high MI values such as for example between Epiphaneia, Antioch, Apamea, and Gindaros or between Nessana, Oboda, and Samaria. Additionally, a handful of sites can be highlighted as potentially informative, such as Tarsos, Gindaros, Gortyn, because they share a meaningful MI value with most sites across the entire dataset.

When comparing with the picture in Roman times, we immediately see fewer zones of interest where MI is high as the entire range of values becomes more compressed. Some notable exceptions are the strong

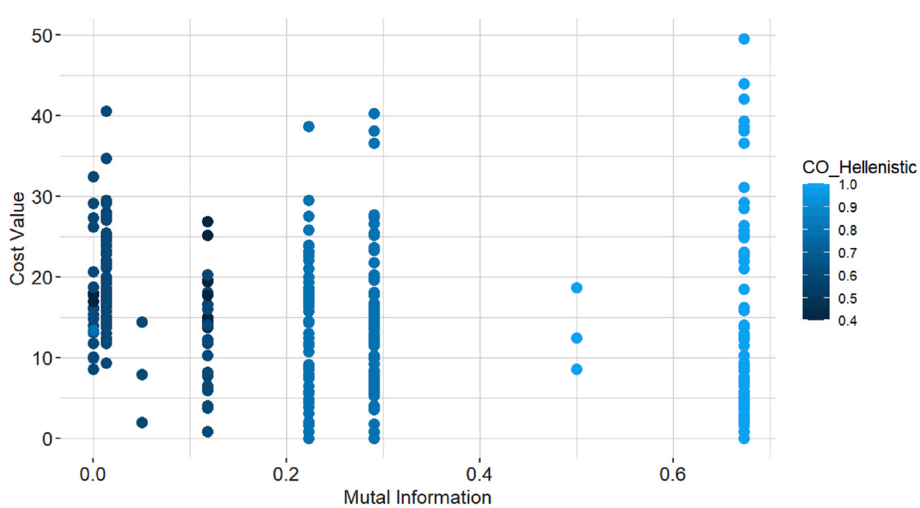

Fig. 6. Scatterplot with MI and cost values for the Hellenistic period. Colouring based on co-occurrence of wares with lighter colours indicating high co-occurrence (made by authors). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

connections between Assos, Troia, Samos, and Ephesos. Interestingly, the site of Pergamon is geographically closely connected with this cluster but does not share high MI values with its neighbours.

These matrices provide some insight into overall patterns, but do not allow us to assess degrees of overlap or co-occurrence in the different pottery wares upon which the analysis is based. In Figs. 6 and 7, we give a scatterplot for, respectively, the Hellenistic and Roman period, showing the MI and cost values per connection between sites, with additional colouring provided by the amount of co-occurrence of wares based on shared presence/absence.

For the Hellenistic period, there is a clear connection between sites with high MI and a high degree of co-occurrence. Moreover, it is clear that this connection holds across the entire range of cost values, meaning that both nearby and distant sites share a strong component of their material assemblages.

For the Roman period, the picture becomes more murky as sites with high co-occurrence feature throughout the entire range of MI values. However, the same observation holds that this connection exists across the entire range of cost values, again indicating that both nearby and distant sites can share a strong component of their material assemblages. This suggests that geographical proximity provides only a partial answer to explain shared distributions of material culture for both the Hellenistic and Roman periods.

In Fig. 8, we show the differences in MI values for the Hellenistic (left) and Roman (right) periods with regard to the cost values (centre) of connections between sites. Inspecting the figure, we can discern strong changes in MI values over time with a highly variable role played by the cost factor, again indicating the limited role of geography as a causal factor.

If we zoom in on a couple of specific instances, it is interesting to note that Carthage, despite great travel costs due to its comparatively distant location, shares a high MI value in Hellenistic times with the cluster of sites in the southern Levant (Petra, Nessana, Oboda, and Samaria). However, the high MI value is not generated by a strong degree of spatial connectivity but rather by the relative marginal positions of these sites within the broader network of exchange at this time. Only the dominant ware of ESA had a network extensive enough to find its way into these areas, whereas the smaller distributions of ESC and ESD only had a marginal presence, resulting in highly similar patterns in the material records of these sites.

Some oddities to be noted are the connection between Carthage and Epiphaneia which is the only connection that has a maximum MI value for both the Hellenistic and Roman periods, which is difficult to find an explanation for at this stage. Likewise difficult to explain is that the pairwise MI between Nessana and Pergamon is the only one that is low in Hellenistic times and high in the Roman period. 207 connections have a non-zero MI for the Hellenistic period and a 0 value in the Roman period, whereas only in 18 cases the inverse holds. Finally, there are 9 connections where the MI value for both the Hellenistic and Roman periods is 0. These connections are related to the specific case of Aizanoi which is completely isolated in Hellenistic times (thus sharing no connections with the other sites) and only has a strong component of ESB in the Roman period, which makes it uninformative for any other site that does not have any ESB.

In Fig. 9, we highlight those connections with a high MI value in the Hellenistic period. Again, it is clear that these occur all throughout the cost value range, indicating the limited role of geographic factors in explaining the networks of trade and exchange in the Mediterranean. Moreover, a high MI value in Hellenistic times does not necessarily yield a similarly high MI value in Roman times, even when costs were low and a high degree of geographical proximity holds, as we see a downward trend in some of the line trajectories. At the same time, we also see a strong component of connections with relatively low costs that retain their high MI values in Roman times (resulting in a V-shaped trajectory)

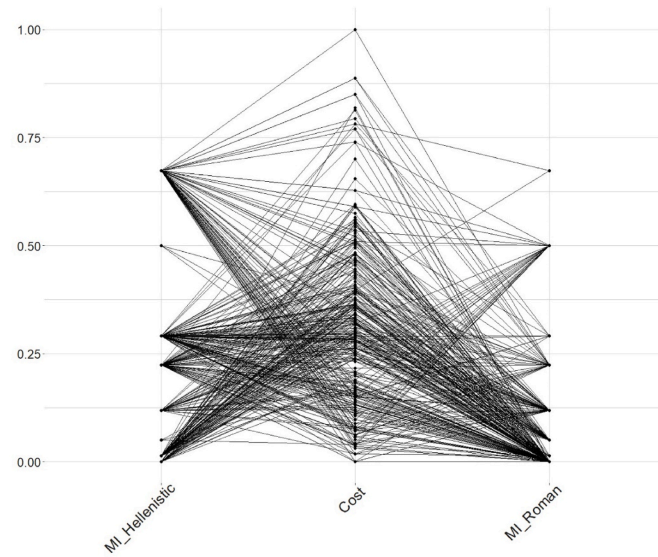

Fig. 8. Difference in MI values for the Hellenistic and Roman periods with regards to cost values (made by authors).

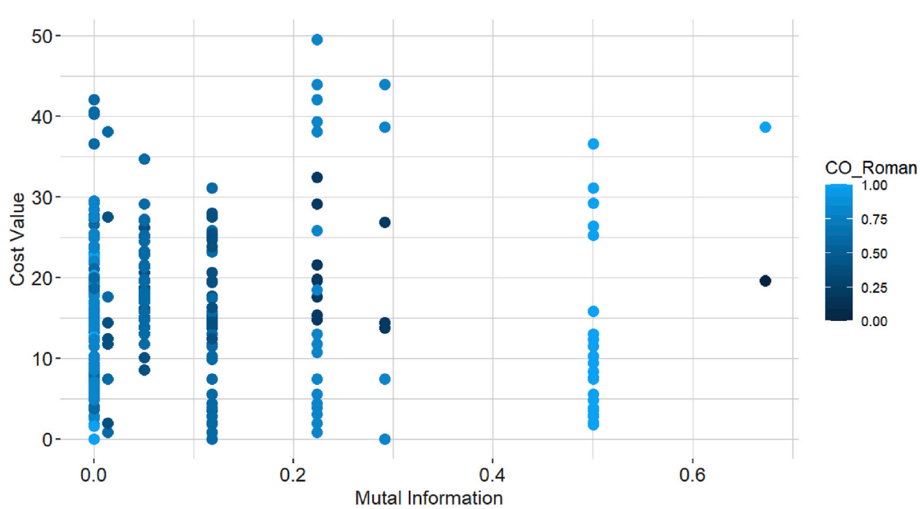

Fig. 7. Scatterplot with MI and cost values for the Roman period. Colouring based on co-occurrence of wares with lighter colours indicating high co-occurrence (made by authors). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

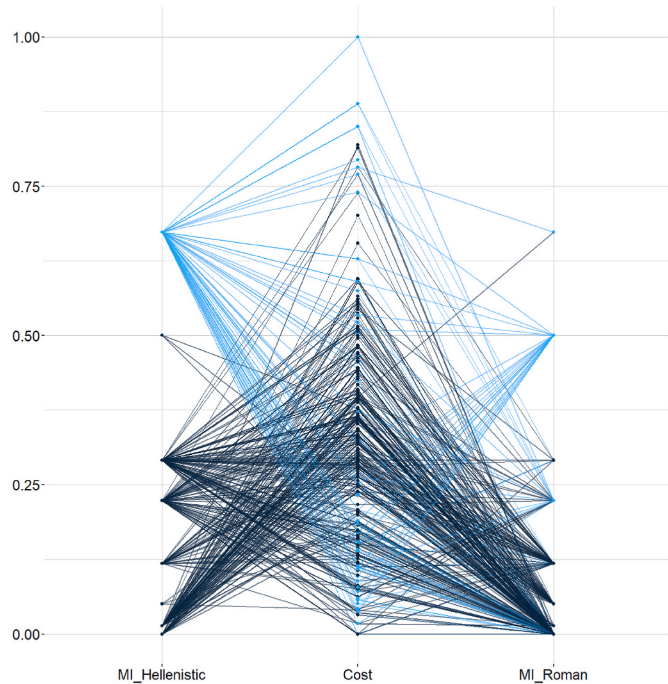

Fig. 9. Difference in MI values for Hellenistic and Roman periods with regards to cost values, highlighting high MI for the Hellenistic period in light blue (made by authors). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

indicating a strong degree of network continuity.

Finally, in Fig. 10, we highlight those connections with a high cost value, defined by the threshold of 1.5 times the interquartile range (a commonly used outlier cut-off). We can note how the connections with the highest costs tend to give high MI values for the Hellenistic period, but less so for the Roman period where a larger variance of MI values is attested, even though a few exceptions of low MI can also be seen for the Hellenistic period. These are again related to the specific instances of badly connected sites such as Carthage, Aizanoi, Petra, and Stobi.

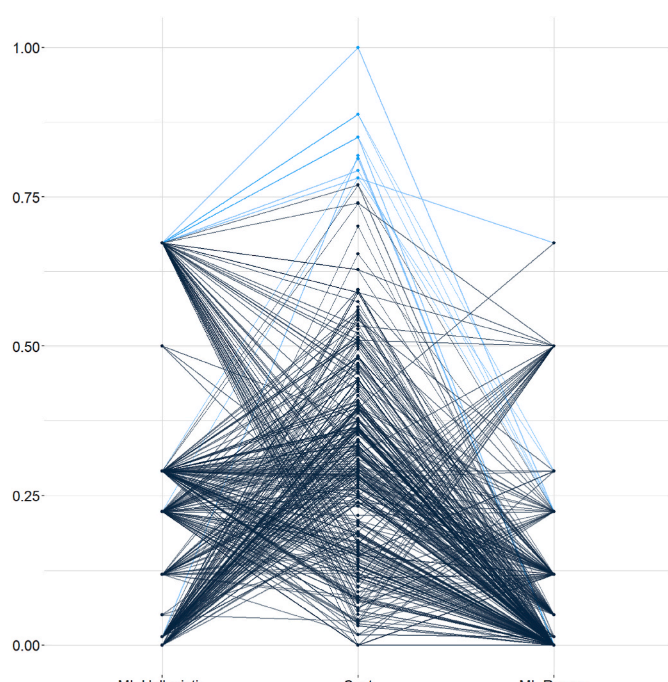

Fig. 10. Difference in MI values for the Hellenistic and Roman periods with regards to cost values, highlighting high costs in light blue (made by authors). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Discussion

The goal of this paper is to present the methodological outlines for an innovative combination of least cost path analysis and mutual information to explore convergences and discrepancies in expected patterns of connectivity and distinguish between geographical and other factors in the distribution of material culture in the Hellenistic and Roman period. Whereas a full assessment of the potential social, cultural, economic, and political processes shaping these networks goes beyond the scope of this paper, we can zoom in on a few cases.

On the level of geographical clusters, our analysis clearly shows strong convergences between sites in the northern and southern Levant. These routes going from Antiocheia and Apamea in the north until Jerusalem in the south were historically part of an important axis of movement by the Seleucid royal court in the second and early first centuries BCE, especially after the loss of territories in Anatolia which prompted refocusing of imperial attention on the coastal Levantine route (Kosmin, 2014, pp. 146–147). The importance of this travel route is underscored by the relatively low travel costs and high MI of the assemblages in the associated cities. It is then interesting to note that Alexandria – despite its relatively modest additional travel costs – shares a distinctly lower MI value with the Levantine sites. Yet, Alexandria has been described the “greatest *emporium* [trade post] in the inhabited world” (Strabo, XVII.1.13) and it would certainly have access to the same trading routes as the Levantine cities. It is tempting – but likely oversimplistic – to associate this discrepancy with the frequent conflicts between the Ptolemaic and Seleucid kingdoms throughout the Hellenistic period.

When looking at the site level, Pergamon can be highlighted in particular. Even though the site is geographically closely connected with a series of other sites in Asia Minor and the Aegean, it does not share high MI values with most of its neighbours as the preference for its own ESC production drowns out the presence of almost any other tableware production attested elsewhere. Finally, a handful of sites can be highlighted as potentially informative, such as Tarsos, Gindaros, and Gortyn, because they share a meaningful MI value with most sites across the entire dataset. The reasons behind this, however, are unclear, and more analysis will be needed to further elucidate this observation.

On a chronological level, one of the main outcomes of the comparison between the Hellenistic and Roman time slices is the overall trend of decreasing MI between sites. This is partially the result of the introduction of two more pottery wares (ESB and ITS) and thus of more variables with potential differences in the Roman time slice (given that the values for these wares will be 0 for all sites in the Hellenistic period). This suggests that as more variables are introduced, the less predictive power any single variable will have, thus muddling the picture as the data patterns become more complex.

An additional observation, however, is that low MI in Hellenistic times is restricted to those sites operating at the margins of the presumed trading networks, most notably Carthage, Aizanoi, Petra, and Stobi. It could therefore be suggested that the increased interaction generated through the political unification and economic integration driven by the Roman state (Verboven, 2021), levelled out some of the differences between the material assemblages of sites. This is reflected not only through more similar material assemblages within regional clusters, but across multiple clusters within the Mediterranean as well.

The observed picture of strongly interconnected clusters held together by weaker ties resemble the small world network structures typical of complex systems (Watts and Strogatz, 1998). In this type of systems, the role of ‘weak’ ties in disseminating information is crucial (Granovetter, 1973). However, it is one thing to observe 'small-world-like' network structures, but another to demonstrate that the system produces the type of behaviour typical of complex (social) networks such as the preferential attachment effect or rich-get-richer type of dynamics in which well-connected nodes tend to increase their connectivity over time. It is tempting to conceive of the transition from the Hellenistic to the Roman period as an example of such a rich-get-richer effect in socio-economic networks in which already well-connected sites such as Pergamon, Athens, or Antiocheia attract a disproportional part of new connections. Exploring these network structures falls beyond the scope of the current paper, but could be an interesting research avenue for future work.

The incorporation of mutual information in this paper entails a marked advantage over more prevalent approaches focusing solely on least cost path analysis, as shared MI values allow us to assess strong and weak ties in the network simultaneously. MI quantifies the amount of information shared between nodes in the network and can therefore help uncovering the efficiency of information transmission across such a network, by shedding light on how information propagates through short paths across local clusters. MI can thus provide a quantitative framework for unravelling connectivity patterns and information flow dynamics that characterize small-world networks and other network structures.

We must also note some potential drawbacks to our approach. Mutual information only takes into account the presence or absence of a variable, rather than absolute or relative numbers of material as would be the case in, for example, similarity measures of material assemblages. The extraction of meaningful insights from complex data patterns through MI therefore comes at the cost of reducing some of the intricacies of material culture distributions. A potential solution to this issue could be found through the combination of MI and similarity networks.

On the ORBIS webpage it is outlined how the ORBIS geospatial model aims to "improve our understanding of how a large-scale system such as the Roman Empire worked". To obtain this objective, the perspective of the model is inherently top-down, "… focusing on the system as a whole. Its simulations prioritize averages over particular outcomes; large-scale connectivity over local conditions; and the logical implications of choices over actual preferences." The analysis performed here through the integration of LCP and MI follows a similar large-scale perspective but also provides a feasible pathway toward uncovering (some of the) underlying bottom-up choices and material culture preferences. An important caveat here is that the scope of the material evidence focused on here is limited in the sense of its restriction to only one type of good. The integration of evidence for other trade goods in addition to tablewares – including grain, wine, olive oil, textiles, building materials, and slaves – holds a great deal of potential for exploring the multi-dimensional and multi-faceted dynamics of trade, exchange, and interaction in the ancient Mediterranean.

6. Conclusions

In this paper, we developed an innovative combination of least cost path analysis and mutual information to trace networks of trade and exchange in ceramic tablewares throughout the (eastern) Mediterranean in late Hellenistic and early Roman times (150 BCE – 50 CE). By exploring deviations from baseline geographical pathways through mutual information as an indicator of shared material assemblages, we sketch the outlines of an approach that can elucidate the potential social, economic, and political factors that underlie the distributions of material culture. Our analysis clearly shows that geographical proximity plays only a partial role in explaining the distribution patterns of material culture. While similarities within geographical clusters are generally significant, important cross-cluster connections facilitated additional transfers of goods, people, and information throughout the Mediterranean. The rise of Rome constituted in this regard only an additional stimulus for integration in an already densely and intensively connected network that characterised the Hellenistic Mediterranean. Through the novel approach proposed here, we hope to pave the way for future research endeavours that seek to unravel the intricate threads of connectivity shaping past and present human societies.

CRediT authorship contribution statement

Dries Daems: Writing – original draft, Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Danai Kafetzaki:** Visualization, Software, Methodology, Investigation, Formal analysis, Data curation.

Data availability

All data is openly available through the mentioned resources. All code and analysis can be accessed through the following repository: https://zenodo.org/records/14063966.

Declaration of generative AI in scientific writing

The authors have used generative AI (ChatGPT) to improve readability and language in certain parts of the introduction and the conclusions. All prompts were based on texts written by the authors and full oversight and control was maintained throughout the editing process. No content-related prompts were conducted or included in the current manuscript.

Declaration of competing interest

None.

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Reproducibility Results

The Associate Editor for Reproducibility downloaded all materials and could reproduce the results presented by the authors.

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