Vestnik drevney istorii
83/2 (2023), 313–339

Вестник древней истории
83/2 (2023), 313–339

DOI: 10.31857/S032103910019357-5

AMPHORA TRACEABILITY IN THE ROMAN WEST: RECOGNITION OF PATTERNS OF COMMERCIAL CONNECTIVITY IN THE ROMAN EMPIRE THROUGH THE APPLICATION OF NETWORK SCIENCE TO AMPHORIC EPIGRAPHY

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Academic research within the humanities has recently witnessed a notable rise in new technologies and in many cases applied to the already ongoing or completed projects. The CEIPAC (Corpus of Amphoras with Latin Epigraphy) has partnered with professionals from other disciplines in a multi-disciplinary effort to collect and manage large amounts of data relating to amphorae and their epigraphic history. Following this research approach, the

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Jordi Pérez González received funding from Juan de la Cierva-Formación-2019 (Agencia Estatal de Investigación (Ministerio de Ciencia e Innovación) REF: FJC2019-040688-I, Ministerio de Universidades en el marco del Programa Estatal de Promoción del Talento y su Empleabilidad en I+D+i, Subprograma Estatal de Movilidad, del Plan Estatal de Investigación Científica y Técnica y de Innovación 2017–2020 (José Castillejo, REF: CAS21/00332) and Grup de Recerca en Arqueología, Prehistòria i Història Antiga (GRAPHA, 2021SGR-00884). Arnau Lario Devesa and José Remesal Rodríguez received funding from the Production and distribution of food during the Roman Empire: Economics and political dynamics (EPNet Project, ERC-2013-ADG 340828, Ex Hispania in Imperium. Interdependencia provincial y dinámicas socioeconòmicas de la producción y comercio de alimentos en el Alto Imperio (PID2021-123951NB-I00) and Dinàmiques socioeconòmiques del món rural romà: formes d'hàbitat i cultura material al litoral central català (II) (CLT009/22/000073). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

members and partners of the research group have been able to acquire a better understanding of the processes of private and public olive oil and wine distribution across the Roman Empire, with special attention to the Empire's Western provinces. This paper represents the culmination of more than seven years of research and aims to present its conclusions to a broad scholarly audience, while also encouraging others to use Data Science in historical and archaeological research.

Keywords: network science, archaeology, Roman Empire, amphora, food supply

ОТСЛЕЖИВАЕМОСТЬ АМФОРНОЙ ТАРЫ В ЗАПАДНОЙ ЧАСТИ РИМСКОЙ ИМПЕРИИ: УСТАНОВЛЕНИЕ СТРУКТУРЫ ТОРГОВЫХ СВЯЗЕЙ В РИМСКОЙ ИМПЕРИИ С ПОМОЩЬЮ СЕТЕВОГО АНАЛИЗА АМФОРНЫХ КЛЕЙМ

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В гуманитарной науке последних лет стало заметно появление и использование новых технологий, которые начали применяться как в текущих, так и в уже завершенных исследовательских проектах. Среди таких проектов оказался и корпус CEIPAC (Corpus of Amphoras with Latin Epigraphy), сотрудничающий с представителями других дисциплин с целью сбора и анализа наибольшего количества данных об амфорах и их истории через анализ амфорной эпиграфики. Междисциплинарный подход позволил исследователям лучше понять, как в Римской империи по частным и государственным каналам происходило распространение оливкового масла и вина. Особое внимание при этом исследователи уделили западным провинциям империи. Данная статья представляет результат более чем семи лет исследований и ставит своей целью познакомить с выводами авторов широкое научное сообщество. В то же время авторы стремятся показать, как data science может быть использована в исторических и археологических исследованиях.

Ключевые слова: сетевой анализ, археология, Римская империя, амфоры, торговля

1. INTRODUCTION

1.1. Network Science Studies in Ancient History and Archeology

Over the past few decades, archaeological sciences have forged ever closer and more frequent relationships with a wide range of disciplines, some of them very different in terms of methodology and fields of knowledge. Nowadays, it is common knowledge that archaeology uses analysis techniques based on physics, chemistry, and geology to establish the age, provenance or other characteristics of all types of material evidence. In general, collaboration with specialists within the STEM disciplines is usually relegated to a very specific phase of the investigation, ideally located

between the collection of material evidence and before attempting an intellectual synthesis of putting the pieces together and extrapolating conclusions.

The rise of data science opens the door to all types of structured information to be subjected to the application of a variety of statistical techniques and machine learning, allowing patterns to be extracted and classifications to be proposed. Meanwhile, the language of complexity, which emerged during the 1970s, has been doing a slow yet valuable job, building bridges between diverse fields of knowledge, and is beginning to also establish itself as a widely used tool in archaeology. The two paths are not mutually exclusive but are based on quite opposite assumptions. Of all the sciences of complexity, network science, a specialty that studies complex relational data, is becoming more prevalent in archaeology, albeit with some difficulties. Network science, or complex network science, emerges from studies carried out in different disciplines and, in short, is made up of a formalism, an analysis toolbox, and an abundance of concrete results[1]. A complex network is nothing more than a mathematical representation of a system in which the components are mapped into abstract objects called nodes (or vertices) and the connections that unite them into links (or edges), regardless of the nature of either. From here on, network science forgets the concrete reality of the system under examination and works with abstract objects. This is why formalism is the common denominator of any research, theoretical or applied, ascribable to this branch of complexity sciences. The typical procedure foresees that, after building the mathematical representation of the system, a characterization of it is carried out by means of the computation of metrics defined expressly for it. Which metrics are most appropriate depends on the context. The most basic ones include the mean number of links per node (degree), the mean minimum length of the path separating two nodes in terms of number of links (average shortest path length), the fraction of closed triangles present in the network with respect to the total of those that could exist (grouping coefficient) and other similar metrics. In the majority of archaeological studies, nodes are representations of the context, i.e. the archaeological evidence, which can be grouped together according to their relative location[2]. But what happens when we work with geographically scattered or decontextualized remains, such as amphora types or ceramic compositional groups? In this case, cluster analysis algorithms can help to classify or group objects based on their individual properties[3].

The application of network analysis in archaeology has not been standardized as an integral part of this field of knowledge, but has nonetheless become quite widespread[4], especially over the last decade, with a growing number of publications in specialized journals.

Although complexity sciences as a whole, and network sciences in particular, have great potential to overcome the rigidity of traditional multidisciplinarity in the interactions between STEM disciplines and archaeological sciences, in practice, the obstacles

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[1] Prigano *et al*. 2022.

[2] Prignano *et al.* 2019.

[3] Prignano, Lozano *et al.* 2017.

[4] There are several overviews of network approaches in archaeology and Roman economy studies: Ahnert *et al*. 2020; Brown 2020; Brughmans, Peeples 2017; 2018; 2020; 2023; Brughmans *et al*. 2014; 2016; Caro *et al*. 2020; Donnellan 2020; Graham, Weingart 2015; Knappett 2021; Remesal, Pérez 2022; Scheidel 2014; Verhagen *et al.* 2019.

obviously do not disappear simply because this overcoming is theoretically possible[5]. For archaeological data to enter the virtuous circuit of network science, the road is by no means smooth. Knowledge of the discipline is necessary, because deep understanding is achieved not only from the new data available, but also with all the previous knowledge of the context, to which must be added a strong specific motivation directed at a certain case of study, assuming a strong initial investment of time and the risk of failure. The ambitious initiative set up by the CEIPAC re-search group at the University of Barcelona aims at developing such interdisciplinary links against a continuous background[6]. The main objective of the EPNet and ERC Advanced grant project 'Production and Distribution of Food during the Roman Empire: Economic and Political Dynamics' was to set up an innovative framework for investigating the political and economic mechanisms that characterised the dynamics of the commercial trade system during the Roman Empire[7]. The latter subject offers a particularly interesting case-study for two major reasons. Firstly, it constitutes a political, economic and social framework that which diverse cultures through conquest, whilst simultaneously using complex social integration initiatives to cope with this diversity. Secondly, the empire represented a system in which a dynamic economy was developed, along with its own mechanisms of interconnection and interdependency.

The core of our research lies in the study of the geographical origins of the products that were transported in the amphorae, economic transactions, and the social positions of and relationships between those who were involved in the trade. The epigraphic record constitutes a body of evidence which has guided this research[8], especially through stamps[9], graffiti[10] and *tituli picti*[11].

1.2. Amphorae trade in the Roman West Frontiers

The first researchers of the *limes* did not pay much attention to the amphorae, despite the fact that Dressel, the father of Roman amphorology, published a synthesis of his results in German over a century ago[12]. Half a century later, Nesselhauf drew attention to the need to study the amphoras found in the Roman frontier area[13]. Modern studies of amphorae in the Germanic *limes* area began with the works of Heukemes and Ettlingen[14] and became more intense following the appearance in 1986 of the work of Remesal, *La annona militaris*, as well as his later work in 1997[15]. At the same time, the work

[5] Prignano, Morer, Díaz-Guilera 2017; Brughmans *et al*. 2019.
[6] Remesal, Aguilera *et al*. 2015.
[7] Remesal, Díaz-Guilera *et al*. 2015.
[8] Prignano, Lozano *et al.* 2017; 2019; Fulminante *et al.* 2017; Martín-Arroyo *et al.* 2017; Morer *et al.* 2020.
[9] Remesal 1986; Rubio-Campillo *et al.* 2017; Moros 2021; Mataix 2019.
[10] Rodríguez Almeida 1990; 1993; Berni 2019; Ozcáriz *et al.* 2020.
[11] Dressel 1894; Rodríguez Almeida 1989; 1994; Aguilera 2000; 2007; Remesal, Aguilera 2014; Mataix 2018; Pérez 2014.
[12] Dressel 1878; 1894; 1899.
[13] Nesselhauf 1960; 1964.
[14] Heukemes 1958; Ettlingen 1977.
[15] Remesal 1986; 1997.

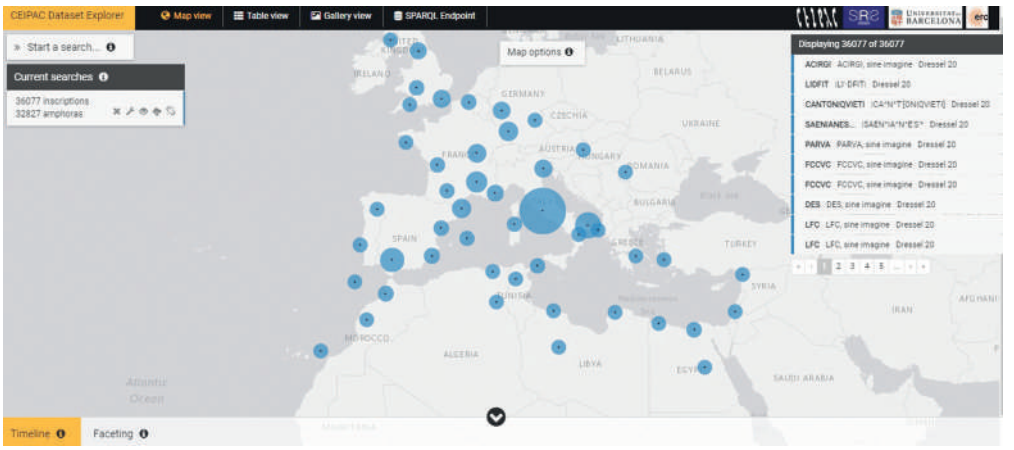

Fig. 1. Geographical distribution. Visualization in Roman Open Data of the geographical distribution of stamped amphoras registered in the CEIPAC database (Data source: http://ceipac.ub.edu; ROD: https://romanopendata.eu). Distribution of 1290 geographical entities of the Roman Empire from the CEIPAC database. Each point represents one archaeological site. Map created using data from Roman Open Data

of Martin-Kilcher[16], Schallmayer[17], Shüpbach[18], Hanel[19], Baudoux[20], Ehmig[21] and Wiegels[22] served as a basic reference for researchers involved in studying the supply of food contained in amphorae to the military stationed on the Roman borders. Here one may refer to the works of Funari[23], Carreras[24], Pons[25], Van den Berg[26], Berni[27], González Cesteros[28], Marimon[29], and Bermúdez[30], as well as Remesal himself[31].

Among the amphorae known in the *limes* area, the Baetican olive oil containers, Dressel 20, are those which offer the greatest opportunities for studying[32]. They are present in most military camps and are the amphoras with which the greatest amount of epigraphic data is associated (fig. 1).

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[16] Martin Kilcher 1987.
[17] Schallmayer 1983.
[18] Shüpbach 1983.
[19] Hanel 1994; 1998.
[20] Baudoux 1992; 1996.
[21] Ehmig 2003; 2007.
[22] Wiegels 2000.
[23] Funari 1996.
[24] Carreras 2000; Carreras, Funari 1998; Carreras, van den Berg 2017.
[25] Pons 2009.
[26] Van den Berg 2014.
[27] Berni 2017.
[28] González Cesteros 2014.; González Cesteros, Berni 2018.
[29] Marimon 2017.
[30] Bermúdez Lorenzo 2017; 2021.
[31] Remesal 2018c.
[32] Remesal 2001; 2011.

The choice of amphoric type is not fortuitous; during the first three centuries AD, the Guadalquivir and Genil Rivers were used as an export route for the amphorae carrying olive oil produced in the province of Baetica, which was sent to many areas of the Roman Empire, especially the Western *limes* and Rome[33]. Today it is in Rome and in particular Monte Testaccio, a Roman age state landfill[34], where more information has been recovered. The unusual conditions of preservation in this site have allowed for a better understanding of a system of stamps, graffiti and *tituli picti* that is far more elaborate than any other known amphora type.

The majority of the studied amphorae were stamped on one or both of their handles with a short sequence of letters and/or symbols, mostly describing one or more *tria nomina* of individuals who were tied to the trade of that product. However, it remains difficult to assess what was the role of this person in the process of production, filling and transporting of the amphora[35]. As they are not unique, these codes can be found in different and usually mutually distant places, so they seem a reliable *proxy* for studying the long-range commercial relations in the ancient world[36].

2. MATERIALS AND METHODS

2.1. Amphorae data

The long-lasting Roman tradition of stamping amphorae has been widely used by researchers to identify trade and ownership patterns for decades, but mostly it has been applied on a local or provincial scale[37]. We use this proxy to establish links between sites in the Western part of the Roman Empire by comparing the similarity of stamps found across thousands of archaeological sites.

The data used for our research come from the Corpus of amphorae with Latin epigraphy compiled by the CEIPAC, which currently contains more than 52,000 entries. The Corpus, which has been online since 1995, is currently being migrated to an ontological system, so that, through the use of metadata, we can interrelate several databases to increase our knowledge and the linking of several aspects of our research. This allows you to recognize the same person in various types of registrations, allowing you to know other businesses, family members and social relevance[38]. The data used in this paper comes from the open access Roman Open Data database (ROD)[39], which is linked to the traditional CEIPAC database, the largest collection of excavated and published amphora epigraphy fragments in the Roman Empire. These fragments have been found at 1680 geographical entities across the Roman territory and belong to 3658 discovery sites

[33] Aguilera 2002

[34] Dressel 1878; Rodríguez Almeida 1984; Aguilera 2002; Remesal 2011; 2018d.

[35] Aguilera 2012.

[36] Rubio-Campillo, Montanier *et al.* 2018; Coto-Sarmiento, Rubio-Campillo 2021.

[37] Bermúdez Lorenzo 2021; Carreras 2000; Carreras, Funari 1998; Carreras, van den Berg 2017; Ehmig 2003; 2007; Funari 1996; González Cesteros, Berni 2018; Mataix 2018; Marimon 2017; Mongardi 2018; Martin Kilcher 1987; Pons 2009; Remesal 1986; 1997; van den Berg 2014.

[38] E.g. Aguilera 2020.

[39] Calvanese *et al*. 2015; 2016; Mosca *et al.* 2015; Palacín *et al.* 2020; Pérez, Bermúdez 2020; Bermúdez *et al*. 2021.

from 39 modern countries, including provincial / regional, territorial and urban divisions. To this total 347 different amphora types can be added.

Similarly, we only take into account the presence or absence of an epigraphic object on a site. Although the volume of marked objects of each production is still unknown and its meaning is debated, the quantitative volume of merchandise and the typological diversity of the ROD data can be significant for learning about the distribution and origin of the food consumed.

2.2. Theoretical approaches to the Network in the EPNet project

The first element to assess is the node, the choice of which poses an initial problem, as there is more than one scale (namely local and global). To solve this issue and homogenise the data, a scale needs to be chosen. Normally, nodes in archaeological contexts are contexts or attributes of contexts grouped together according to their context. In our case, we consider amphoric types or ceramic compositional groups which distinguish a continuous spectrum of differences.

Connections are the other main part of a complex system, and in our case they present a broader repertoire of issues. The link between one node and another depends on their interpretation, since what defines the meaning of a connection is the research hypothesis. In this case, since direct observation is out of the question, the links need to be inferred. Nodes are thus social groups associated with places and connections are interactions defined by concrete processes, in our case the trade on olive oil.

Although theoretical approaches might indicate otherwise, it is expected that some groups of archaeological sites (clusters) are more similar to each other than to any other node in the complex system. Those groups can then be analysed as a community, so the interactions between "similarity groups" are visible in the physical expression of the complex system. We chose to measure the similarity between these sites by means of the Brainerd-Robinson (BR) coefficient because its definition is intuitive and it was developed within archeology specifically for comparing assemblages in terms of the proportions of types or other categorical data. BR is a city-block metric of similarity that is calculated as:

$$BR(i,j) = 200 - k = 1pP_{ik} - P_{jk}$$

Eq. Brainerd-Robinson coefficient[40]

where, for all categories (k), P is the total percentage in assemblages i and j. This provides a scale of similarity from 0–200 where 200 denotes a perfect similarity and 0 a total absence of similarity. We chose this system because its definition is intuitive, and it was specifically developed within archaeology for comparing assemblages in terms of the proportions of types or other categorical data.

We first tested our approach to the network science on our main case study, the Germanic provinces, and the broadest geographical area possible, the entire Roman empire. In these cases, rather than similarity, it was dissimilarity which was used to analyse the datasets. The dissimilarity between two sites was based on the number of stamp codes which were present on one location and absent on the other one. This was quantified

[40] Robinson 1951.

with the Jaccard distance[41]. The distance between the sets of codes c_i and c_j as collected in a pair of sites *i* and *j* is defined as the ratio between the number of codes found in both sites and the number of codes which are found in at least one site, as can be represented in the following equation:

$$\boldsymbol{D}_{Jaccard}(\boldsymbol{i},\boldsymbol{j}) = 1 - \frac{|c_i \cap c_j|}{|c_i \cup c_j|}$$

Eq. Jaccard distance

The Jaccard distance is bounded between 0 (in which the sites have exactly the same stamp codes) and 1 (in which the sites do not share any code). The average distance was close to 1 as most of the sites had a small number of unique stamps[42].

In the case of the Monte Testaccio, another system was used regarding the traceability of the amphorae and its content: the asymmetric index.

The modified asymmetric index from *A* to *B* is defined as:

$$O_{A\to B} = 2\frac{S_A}{N_A}\sum_{i=1}^{k}\min(Q_{iA}, Q_{iB})$$

From B to A, this presents itself analogously as:

$$O_{B\to A} = 2\frac{S_B}{N_B}\sum_{i=1}^{k}\min(Q_{iA}, Q_{iB})$$

Eq. Asymmetric index

$O_{A\to B}$ indicates the superposition of *A* with *B* and $O_{B\to A}$ the superposition of *B* with *A*. ^{k} denotes the number of existing boxes and S_A (or S_B) the quantity of objects of the class *A* (or *B*), where there are objects of the class *B* (or respectively *A*). In other words, when we are looking for an association of a certain *titulus pictus A* with a stamp *B, SA* corresponds to the number of *tituli A* that have appeared in the boxes where we have found the stamp *B*. N_A denotes the total number of objects of the class *A* found in the excavation. Q_{iA} denotes the quotient between the number of objects *A* in the box *i* and the total number of objects of both classes *A* and *B* in all the boxes where they coincide. Q_{iB} and N_B are defined similarly[43].

The following example shows the idea of this index. Let us consider an excavation where it has been found the object *A* and the object *B* in the following form.

A A B		A	
		A	A
B A		A	
	B A	B A	
			A B

The objects are classified in different boxes. One can observe in this example that *B* is found with *A*, but *A* is not found always with *B*. In this case, $O_{A\to B} = 6/11$ and $O_{B\to A} = 10/11 = 0.91$. *B* coincides with *A* almost in its totality, for reaching that 100% it is necessary another object *B* in the left box placed at the top.

[41] Jaccard 1901.
[42] Rubio-Campillo, Montanier *et al.* 2018.
[43] Ruiz *et al.* 2018.

3. RESULTS

3.1. Case studies

Four examples are proposed to test whether the inclusion of *Network Science studies in Epigraphy and Archeology* offers productive results.

1. The first has to do with the analysis in Big Data format of the epigraphy of olearian amphorae distributed on a *continental* level, and especially in the western Roman Empire.

2. The second example offers a *provincial* vision to visualize its intraprovincial distribution.

3. The third case analyzes *local productions*, in this case of wine amphoras produced in the vicinity of the Llobregat river (Barcelona, Catalonia, Spain) and the question of productive links.

4. The fourth case has to do with an archaeological survey, that of the *Monte Testaccio*, where it is tested whether there is a possibility of linking epigraphs.

For the development of the networks of the first three study cases, the Brainerd-Robinson coefficient is applied and for the particular case of Monte Testaccio, the Asymmetric index is applied.

3.1.1. Continental level: a group effort

The first of the case studies analyzed has been possible thanks to the cumulative (and decades-long) effort of amassing thousands of data, with the publication of Remesal's book on *annona militaris*[44], in which a catalogue of the materials from the Roman provinces Germania was included, in 1986 representing a starting point. Years later, new materials from the region were incorporated in Remesal's second monograph[45] without alteration initial hypotheses[46], and in parallel the digital corpus of CEIPAC was created[47]. The digital corpus was the ideal place for the union of the later investigations dedicated to the study of other Roman territories. In this connection, it is also worth highlighting various studies which correspond to the research principles of our group, such as Funari and Carreras for Roman Britain, Pons in Mauretania Tingitana, Garrote and Marimon in Gallia Narbonensis and in Gallia Lugdunensis respectively, Bermúdez in Raetia, and the works of Berni and Moros on places of production[48].

The hypothese advanced in 1986 about the existence of the Atlantic route as a way of supplying food for the army on the north-western Roman border[49], was mathematically reaffirmed by the work of Rubio *et al*. 2018a; 2018b. Observations in unpublished network built from all the stamps on Dressel 20 olearian amphorae offer very similar results. As a result, the groupings of materials by similarity in these networks show how the settlements of the same province or region share similar epigraphs. Here we have applied

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[44] Remesal 1986.
[45] Remesal 1997.
[46] Remesal 2018b.
[47] Remesal 2012.
[48] Barea *et al*. 2008; Bermúdez Lorenzo 2021; Carreras 2000; Carreras, Funari 1998; Funari 1996; Garrote 2016; Berni 2008; 2021; Marimon 2017; Moros 2021; Pons 2009; Remesal, Moros 2019.
[49] Remesal 1986.

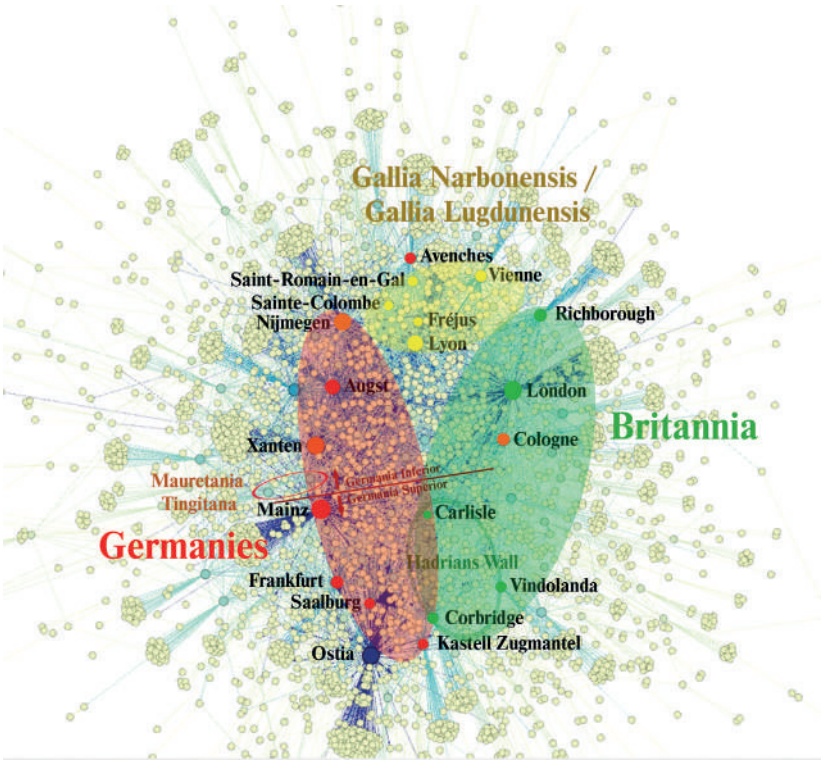

Fig. 2. Roman Empire trade areas. Network built with more than 10,000 stamps on Dressel 20 olive oil amphoras, excluding Rome and Golfe-de-Fos from the sample. Provincial consumer groups are indicated in colors. Network created using data from Supporting Information

the classical construction developed in several of our EPNET works, such as the 'Places of Findind' and 'Epigraphy'[50]. The blue nodes represent a place and the white nodes represent the various types of stamps (fig. 2), where the size of the link is proportional to the number of elements (stamps) in it. Similarly, the size of the nodes representing the places is proportional to the number of stamps found in these locations[51].

In order to adapt the data to the question raised here, we have filtered all the stamps on the Dressel 20 amphoras outside their place of production, ignoring the materials found in the Roman province of Baetica (see Supporting Information for Dressel 20 epigraphy). This allows us to focus the results on distribution and not on production[52]. Thus, the network generated includes the configuration of more than 16,000 stamps. First, the visualization of the information confirms the existence of several related communities through larger nodes which show the existence of stamps with the same reading, together with epigraphic singularities found in specific places, which generates subgroups associated with a single place. In parallel to these sets of stamps, there are a number of

[50] Prignano, Morer *et al.* 2017; Pérez *et al.* 2018.
[51] Pérez *et al.* 2019.
[52] Berni 2008; Bourgeon 2021; González Tobar 2020; Moros 2021.

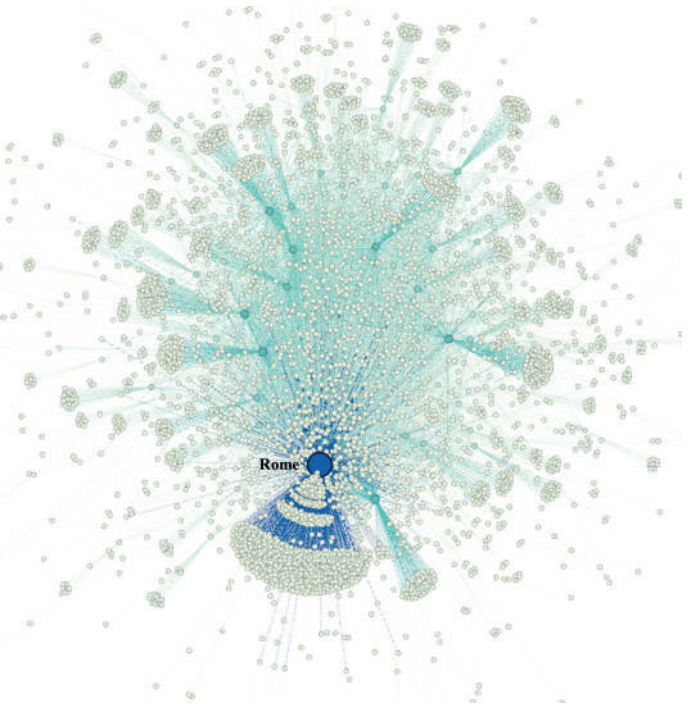

Fig. 3. Roman Empire amphora distribution. Network built with more than 16,000 stamps on Dressel 20 type oleary amphorae. The consumer capital of Rome is indicated. Network created using data from Supporting Information

peripheral nodes which show a certain tendency towards isolation compared to the general macro-structure. We might explain this either because they are places with few epigraphic samples, or because they possess a certain geographic isolation, or because they preserve epigraphs that are difficult to read or incomplete due to their lamentable state of conservation or high degree of fragmentation.

The results obtained show one hub which is greater than the rest and with greater connectivity to the rest of the community, namely the city of Rome (fig. 3). Given this, it is crucial to understand the capital as the most important olive oil consumption center. We may also include here the large amount of data pertaining to the excavations at the Monte Testaccio state landfill[53], to which we will return later, as a second filter on the data, whilst ignoring a third of the sample (more than 6500 stamps) in order to assess the regional groupings as a more balanced network. Certainly, Rome as the imperial capital concentrated products from all regions. However, the existence of Monte Testaccio shows that there was a state intention to store olive oil in the Tiberian port region to support the roman population. On the other hand, the distribution of olive oil throughout the West and

[53] Remesal 2019.

in particular, on the Rhineland-Danubian frontiers show the extent to which the State was concerned with supplying Rome with a basic food product in the Roman diet[54].

Consequently, the resulting network is more compact and allows us to observe in finer detail the existence of binding epigraphic sets between the various regions of the Roman Empire. This trend agrees with the presence of a series of places which seem to act as centers in the distribution of these territories or provincial hubs[55]. Among them the following places stand out: Avenches, Augst, Corbridge, Frankfurt am Maim, Fréjus, Cologne, London, Lyon, Mainz, Nijmegen, Ostia, Saalburg, Saint-Romain-en-Gal, Sainte-Colombe, Vienne, Vindolanda and Zugmantel. In these cases, if we added the information related to the Roman provinces, we could visualize the different groupings caused by the regional structures of distribution and food consumption. Leaving aside the node of the place of Ostia, as a port city linked to Rome, the communities would be divided between both Germanias, the Superior (Avenches, Augst, Frankuft, Mainz, Saalburg and Zugmantel) and Inferior (Cologne, Nijmegen and Xanten), Britannia (London, Corbridge and Vindolanda) and Gallia Narbonensis (Fréjus) and Lugdunensis (Lyon, Saint-Romain-en-Gal, Sainte-Colombe and Vienne). This case study would generate very similar patterns to those already highlighted in Rubio *et al*. 2018a; 2018b. There the results confirm that the provincial structure played a relevant, if not decisive, role in the organization of the olive oil trade to the border provinces. Particularly important is the pattern of similarities between the Atlantic provinces (Britannia, Germania Inferior, Germania Superior and Mauretania) and the supply route that would have the Rhone as its driving axis (cf. fig. 2).

From the case presented, there are two scales for testing the similarity in the patterns from which the previous hypothesis was derived. At a macro level, if we group together the provinces[56] that we could refer to as Atlantic (Germania's, Britannia and Mauretania Tingitana) on the one hand, and the Gallic provinces, structured by the Rhone River (Narbonensis and Lugdunensis), on the other hand, we would see that there is a clear difference between both structures, which associate more with each other than as a whole. At the same time, a detailed vision allows some characteristics of these communities to be highlighted. For example, in the grouped data of both Germanias we might differentiate between the Inferior and the Superior and in Roman Britain set we can point out the community linked to Hadrian's Wall. Perhaps this has to do with the temporary flows of distribution or the specialized consumption of certain producing regions in Baetica. It is also very possible that imperial administration promoted the supply of the various border areas based on their activity, a policy often linked to a war economy[57].

Once the inscriptions have been temporarily contextualized and assuming the finiteness of each lot of stamps, we can perceive differences between the materials found in Germania Inferior and Superior. This could be related to the border activity itself: the former relates to an earlier conquest during the first century AD, while the latter shows

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[54] Remesal 1986; 1997; 2011; 2018c.

[55] Milgram 1967.

[56] On spatial networks, see e.g. Donnellan 2020. On ceramic distribution networks, e.g. Brughmans, Poblome 2016. About the Distribution Patterns, also see RGZM Mainz on terra sigillata: https://www1.rgzm.de/transportroutes.

[57] Remesal 2018c.

great activity during the second century AD before the abandonment of the frontier at the entrance of the cross-border towns[58]. These findings could be extended to explain very homogeneous sets of materials on the northern borders of Britannia[59] or in Mauretania[60], which were probably the result of the need in the supply of specific moments or specialization in the importation of amphorae produced in particular potteries. This would also help to make sense of the relationship of Mauretania Tingitana with the rest of the Atlantic provinces[61].

At the same time, there are some noticeable exceptions in the network of some of these hubs that are only understood by their hybridization in the supply routes or by sharing common temporary spaces. For example, places such as Cologne[62] in Germania Inferior have more in common with places such as London (Britannia)[63], perhaps because they share a similar similar dynamics in the development of food (in this case, olive oil) during the conquest and the period of stabilization[64]. Along these lines, we believe that the greater similarity between places like Avenches or Augst, south of Germania Superior, and Gallia than with the rest of the Germania Superior settlements can be interpreted as reflecting their place in a common supply network. This supply route would have the Rhone as its driving axis for reaching the centre of Europe or for other products in the first decades of the Roman expansion. Hence, the network shows some similarity to the materials found in the area of Gaul where the Rhone runs or its vicinity[65].

3.1.2. A provincial approach

The mapping of provincial networks from the epigraphy found there originated from the interdisciplinary research conducted within the framework of EPNet[66]. The central objective of these networks was to understand the evolution of the connectivity which characterised each province in the final phase of the amphorae's traceable history. The method developed above by the network scientists provided the project's historians and archaeologists with an easy-to-use tool for analyzing large data sets as never before. Although it is an adaptation of the existing tools in Network Science to a particular case and data, it deals with characteristics that can easily be found in other case studies in Classical Studies[67].

As in the previous network, the categories analyzed are related to the stamps and their places of discovery. From Prignano, Lozano *et al.* 2017, a total of four provincial networks have been developed in order to analyze their data and validate the method. The first three

[58] Remesal 1986; 1997.
[59] Ayllón *et al.* 2019.
[60] Pons, Berni 2002; Pons, Pérez 2018.
[61] Rubio-Campillo, Bermúdez *et al.* 2018; Rubio-Campillo, Montanier *et al* 2018; Pons, Pérez 2018.
[62] Remesal 1997; 2018c; Mayer 2016.
[63] Funari 1996; Carreras, Funari 1998.
[64] Remesal, Bermúdez 2021.
[65] Rubio-Campillo, Bermúdez *et al.* 2018; Rubio-Campillo, Montanier *et al* 2018; Coto-Sarmiento, Rubio-Campillo 2021.
[66] Prignano, Lozano 2020.
[67] Prignano, Lozano 2020.

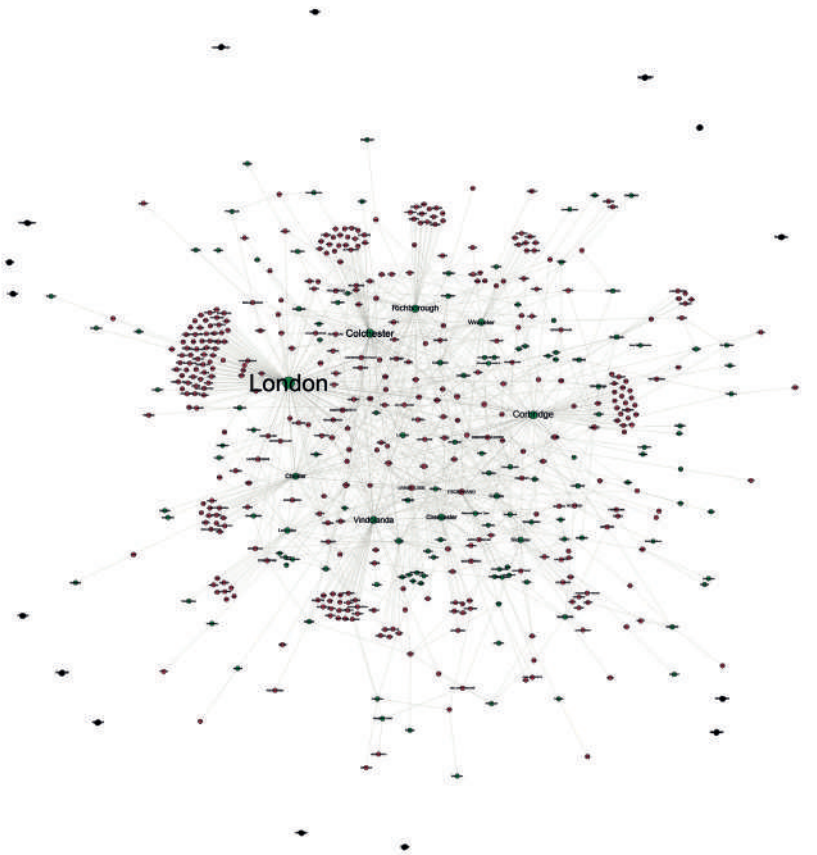

Fig. 4. Consuming Roman Britain. Consumption and distribution network of nearly 2000 stamps on Dressel 20 olive oil amphorae in the Roman province of Britannia. In green the reception places and in pink the stamps represented. Network created using data from Supporting Information. For the rest of the cases see the same file

have focused on the frontier zones of Germania Superior, especially the Roman forts of the northern section, between the Rhine and Main rivers, of Germania Inferior[68], and of Mauretania Tingitana[69]. Finally, a comparison between the results in Britannia and in these three provinces were made (fig. 4), together with a detailed mapping of the northern frontiers of the province, with Hadrian's Wall and the Antonine Wall serving as receiving centers for Baetican olive oil[70] (see Supporting Information for all).

Again, the temporality of the stamps, as well as their origin, are features which help to understand the exposed results. Although the conquest and stabilization of the territory that later became the province of Germania Inferior was earlier than that of its

[68] Remesal 2018a.
[69] Pons, Pérez 2018.
[70] Morvan *et al*. 2017; Ayllón *et al*. 2019; Pérez 2019; 2022.

eastern homonymous counterpart, Germania Superior, it is normal that stamped amphorae share intra-provincial features more than extra-provincial features. These waves of warfare on the borders required imperial supervision, in order to meet the needs of each moment. The Germania Inferior network, with its greater presence of materials between the Julio-Claudian and Flavian-Trajan periods, shows a compact situation as well as heterogeneous results. On the one hand, a solid network appears to connect these places, headed by Colonia Ulpia Traiana (Xanten), Nijmegen and Cologne, which had greater military capacity and which were better known for their excavations, but on the other hand there are a large number of stamps that are only found in one of these places[71]. The existence of some stamps with a greater presence and concomitants between the various places may suggest a greater specialization in the distribution of oil controlled by one or more certain agents than is currently unknown in the limes, as long as it is accepted that they are the characters reflected in the beta *tituli picti* of these amphoras.

In this connection, the similarity between the provincial networks is remarkable, even highlighting certain singularities such as those observed in the Germania Superior network, where there is a greater link between the places of Saalburg, Zugmantel (Orlen) and Frankfurt am Maim-Nida-Hedderheim than with Mainz. Perhaps this fact can be understood as a result of the greater proximity between the first camps, which stood on the front line of the border, as opposed to the place of Mainz, whose nucleus had a greater epigraphic presence in the border rear and which could have been part of a different supply network. This hypothesis has already been defended in the particular case of the Britain limes at Hadrian's Wall by Ayllón *et al*. 2019, who propose that the places of Vindolanda, Carlisle and Colchester, located in the stanegate, perhaps acted as centers of consumption and distribution of the first border line[72]. In the case of both borders, whenever possible, the river directed the supply to the interior, while at the same time acting as a natural border: on one side was the river Rhine (Tac. *Ann*. 2.6.2)[73] and on the other the isthmus of the Tyne-Solwey rivers (for Hadrian's Eall)[74] and Forth-Clyde (Antonine Wall)[75].

Furthermore, the war activity in these regions can be distinguished through the proposed networks thanks to the homogeneity of the epigraphy found there. For example, the grouping of stamps found on the Mauretanian, Rhenish or northern borders of Roman Britain is clear and allows one to distinguish between the supply of both walls in this last province and their different chronological uses, which perhaps relates to logistics directed during a period of growing conflict[76]. It must also be borne in mind that we know the date of the founding and disappearance of the camps despite the fall of many sections of the limes, which can help us to attribute a post-quem and ante-quem date to the amphorae. On the other hand, amphoras can help us to date various chronological moments between these two extremes.

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[71] Remesal 2018a.
[72] Ayllón, Pérez 2014; Ayllón *et al*. 2019.
[73] Remesal 2018c.
[74] Ayllón *et al*. 2019.
[75] Pérez 2022.
[76] Ayllón *et al*. 2019; Pérez 2022.

3.1.3. Local production.

The third case study focused on understanding, through the construction of networks, the productive links of several of the best-known wine amphora types in the province of Hispania Citerior (Tarraconensis). From the north-east of the peninsula come about 2700 stamped amphoras that are recorded in more than 160 publications of the last 70 years[77]. Among these stand out the amphoras Pascual 1, Dressel 2–4 Tarraconense vel Dressel 3–2, as well as the Oberaden 74[78]. This corpus offers many possibilities for mapping the production and consumption of wines made in the region, but the high percentage of finds in the territory itself, numbering close to 60%, compels us to pay special attention to its production organization chart. Continuing with the construction of epigraphic networks, a mapping of the potteries located throughout the Maresme region and the mouth of the Llobregat river was proposed, focusing on the deposits of Castellbisbal, Papiol and Sant Vicenç del Horts (see S2).

The elaborated network shows a very unequal distribution of the stamps and little or no variability between the different places where they was produced. In other words, the stamps presented in each pottery-site are different and the network does not indicate a connection between the various centers. Hence, we surmise that the producers are very independent from each other (for networks and data, see Supporting Information). The analysis of the network helps to understand the organization chart of these workshops. Comparing it with the study of the massive oil productions of the Dressel 20 type in Baetica, the results show certain similarities but highlight the independence of each pottery site, which had its own sealing system[79] or punctual connections[80].

At the same time, regardless of the meaning of these stamps and their relationship between pottery sites, it would be interesting to replicate the study with the graffiti found in the region, which can help us better understand the phases of the workshops and the question of the existence or not of a mobile collective of artisans among the various potteries[81].

3.1.4. The archaeological excavation of Monte Testaccio (Rome)

The last case study focuses on the materials found in the excavations of Monte Testaccio (in Rome). Monte Testaccio is located in the plain below the Aventine Hill, is currently 50m high by 1km in perimeter and is the remainder of a state amphora dump (1st-3rd century AD) (see S3). It contains the remains of the amphorae in which the olive oil bought by the Roman state or received as taxes arrived in Rome and which served to keep prices stable in the city's markets[82]. This subsidized olive oil served, along with the grain that was distributed in part without cost, to oppose as much as possible the uprisings of the population[83]. It therefore represents a particularly significant example insofar as it is a state dump

[77] Palacín 2018; 2022; Palacín *et al.* 2020; Martín i Oliveras *et al.* 2022.
[78] Roman Amphorae: A Digital Resource. URL: http://archaeologydataservice.ac.uk; accessed on: 13.05.2023.
[79] Rubio-Campillo *et al.* 2017; Coto-Sarmiento *et al.* 2018; Coto-Sarmiento, Rubio-Campillo 2021.
[80] Moros 2014; 2019; 2021.
[81] Berni, Miró 2013; Berni, Revilla 2008; Miró Canals 2020.
[82] Aguilera 2002.
[83] Remesal 2011.

of oil amphorae in the port area of the old imperial capital, where there is neither land nor well-defined strata but only amphoras and more amphoras[84]. In recent excavations, an artificial system has been excavated, whose soundings have been divided into sections of 1 m^2 from which materials of 20 by 20 centimeters can be extracted[85].

The statistics produced so far quantify the origin of these amphoras from the Baetica province, in particular those of the Dressel 20 type, by about 85%. The accumulated knowledge allows us to ensure that the shipments of olearian amphorae, which one day left together from Baetica, arrived, at least in part, together as far as Rome. Once emptied in the port area reserved for it, we have proposed that these amphoras were uploaded to the landfill in sets of four on the back of a cavalry (when empty, these amphoras weigh about 30 kilos each; 120 kilos is a standard load for a cavalry). After being off-loaded at the ceramic dump, they were broken right there to take advantage of the space used while others were used to build the walls, as if it were a stepped pyramid. As a rule, it is common to find fragments that sometimes join within our artificial strata and sometimes with fragments of other neighboring strata. Thus, the knowledge of the formation of the mount allows us to state that the natural strata have a power similar to the maximum diameter of our amphorae (about 60 cm). Since we excavated 20 by 20 centimeters, at least three of our levels should correspond to one of the natural strata. However, since we do not normally find these walls, we compare the materials of each of the strata with two upper strata or as many lower ones so that we can establish relationships theoretically between the materials of the strata defined by us, and thereby determine which ones correspond to a "natural stratum" of Monte Testaccio.

In addition to the stamps, there are also graffiti *ante cocturam* and the painted inscriptions known in scholarship as *tituli picti*. The latter inform us of the tare of the amphora (alpha), the net weight of the olive oil content (gamma), the name of the person responsible for the commercialization or transport of the amphote (beta), and the customs-fiscal control where the fiscal district in Baetica is indicated from which the amphora was issued, confirmation of the content, those involved in the control and the date of the year of commercialization of the amphora (delta). This allows us to possess an abundant series of documents that are dated with precision (a rare fact in the documentation of the Roman world). Our efforts since 1989 have been to unite the maximum number of fragments of the same amphora in order to recompose the greatest amount of information contained in them, and thereby know as much as possible about the traceability of the distributed object[86].

So far we have represented in our publications the relative positions of the stamps and *tituli picti* found in each of our surveys. By mapping our surveys in the form of a network, we hope to apply new methods in order to better relate our various materials and establish-a better correlation between our materials. To do this, we have selected the surveys of the years 2000 and 2005[87], where we will apply the asymmetric index mentioned above.

[84] Pérez *et al.* 2018
[85] Blázquez *et al.* 1994; Blázquez, Remesal 1999; 2001; 2003; 2007; 2010; 2014.
[86] Pérez *et al.* 2018; Ruiz *et al.* 2018.
[87] Blázquez, Remesal 2014.

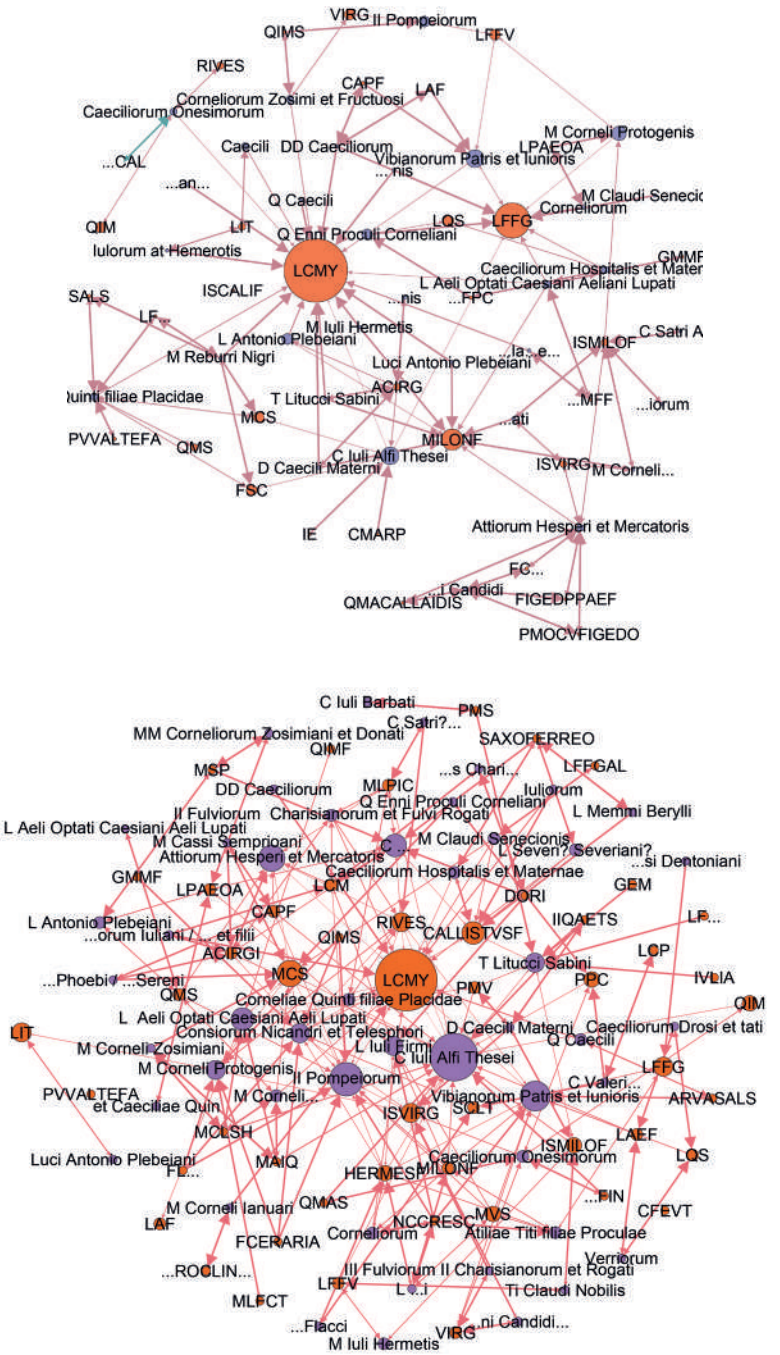

Fig. 5. Links between olive oil production and marketing. Network of stamps and *tituli picti* beta in the 2000 and 2005 exavation campaigns at Monte Testaccio (Rome, Italy). 293 stamps and 289 *tituli picti* beta (out of a total of 1464) have been used. The data from the 2000 survey are shown at the top and the 2005 data at the bottom. The stamp is represented in orange and the beta in purple. Network created using data from Supporting Information

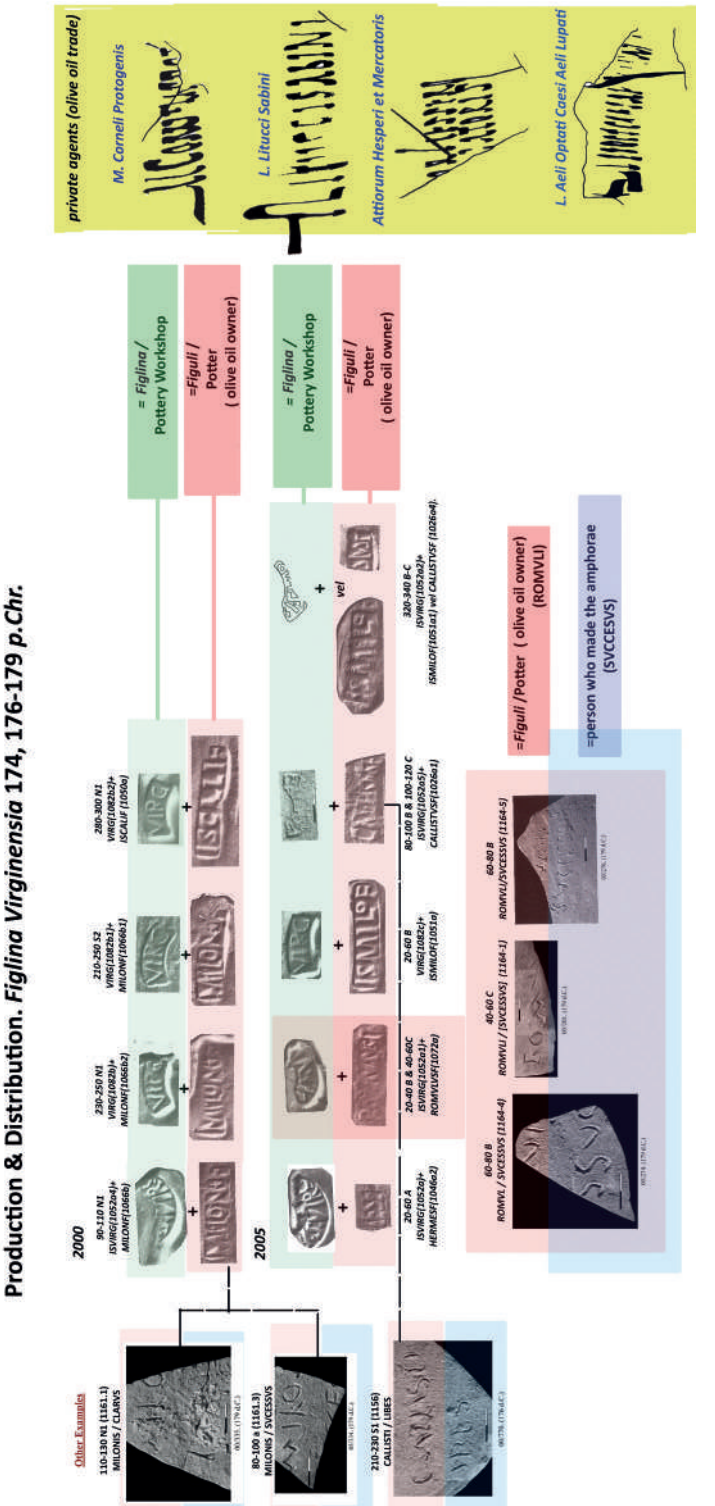

Fig. 6. Proposed traceability of Figlina Virginensia (years 174, 176–179 AD). Representation of a probable producer organization chart and the commercial distribution of private agents based on the network of similarities. The pottery is found in Villar de Brenes (Brenes, Spain) in the Roman province of Betica, and was discovered in the excavations of the years 2000 and 2005 in Monte Testaccio with dates from the years 174, 176–179 AD (Blázquez, Remesal 2014). Network created using data from Supporting Information

The construction of a network of different types of inscriptions formed by stamps (in orange) and *tituli picti* beta (in purple) reveals the similarity between the various groupings of epigraphs (fig. 5). At first glance we can already see the existence of groups of stamps from the same place in Baetica, a pottery center known as *Figlina Virginensia*. In this connection, the ISVIRG, ISMILOF or MILONF (year 2000) or ISVIRG, HERMES, MILONF or ISMILOF (2005) stamps were produced during the second productive phase of the workshop (here represented by the years 174, 176–179 AD) and their distribution throughout the capital could be assumed to be extensive. Along with this community of stamps a series of characters (in the amphora position known since H. Dressel as *beta*) also appear that could once be part of the same object (for the results of the surveys of the 1993, 1997, 2007 and 2010 publications, see Supporting Information).

Without the need to develop the productive organization chart of *Figlina Virginensia*, which is widely known[88], and setting aside the combination of the message divided into stamps by their *cognomina* and toponyms[89], the association of the characters who are believed to have made these amphoras are represented in a set of unique graffiti from the workshop, where the name of the amphorae appears in the second line and the orders of the *figuli* / potter (olive oil owner) in stamp. To all this we can now add, thanks to the proposed method, the link with several of these agents in *beta* who were dedicated to the commercialization or distribution of amphorae in *Virginensia* (fig. 6), which included *M. Corneli Protogenis* (2000 and 2005), *L. Litucci Sabini* (2005), *Attiorum Hesperi* and *Mercatoris* (2000) and *L. Aeli Optati Caesi Aeli Lupati* (2005). A proposal on its traceability is given below:

4. DISCUSSION AND CONCLUSION

In 1986, Remesal proposed that since Augustus there had been an organized military supply system for the administration of the empire. This led him to a more general study of the Roman annonary system, and how it influenced not only the economic evolution of the empire, but also its political evolution[90]. Thus, the imperial administration did not need large amounts of cash to cover the tax and supply needs of the state structures, among which was the army, and thanks to accepting the interprovincial food supply, it covered part of their needs. According to his calculations, the state retained two thirds of the salary assigned to the soldiers, and thus the army in fact functioned, economically, with a much lower volume of cash than theoretically calculated[91].

The results presented here are surprisingly similar to the theoretical models of appraisal and coinage flows by Keith Hopkins (further developed by John K. Davies) for the Roman Empire, who displayed this model graphically with a simplified diagram of three circles, one within the other, symbolising geographic space divided into regions, which derive their significance from political spheres: ‘centre’, ‘middle zone’ and ‘periphery’

[88] Berni 2008; Pons, Berni 2002; Pons, Pérez 2018.
[89] Moros 2021.
[90] Remesal 1986.
[91] Remesal 2011.

or 'frontier'[92]. For this, we must understand the supply of olive oil as a tax-exchangeable product, where Baetica must be recognized as a producing province of the middle zone, destined to first supply the food needs of the citizens of the capital of the Empire – the centre – to control its political influence, and then the borders – the periphery – where thousands of soldiers secured the Roman territory. Rome, like all empires, benefited from exploiting the resources of the territories they conquered, integrating them as producing and consuming provinces.

For this reason, the study of the amphorae material offers a new perspective: the survival of the limes depends on the supplies that arrived from other provinces[93]. The task that we have set ourselves to present here is to delimit the following: which provinces, and at what time, formed the base of support for the limes; what relations were established between the different provinces; how they were related to each other; what role the imperial power played in the relations between the various provinces; and how each of them influenced the political evolution of the empire.

Supporting information

Source code and datasets are available under Open licenses and can be freely accessible from
URL: http://dataverse.csuc.cat/privateurl.xhtml?token=48398465-858f-4013-8701-537c8a99462a; accessed on: 13.05.2023.
DOI: https://doi.org/10.34810/data138; accessed on: 13.05.2023.

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[92] Hopkins 1980; Hopkins, Kelly 2018; Davies 2005; Jogman 2018.
[93] Remesal 2018c.

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