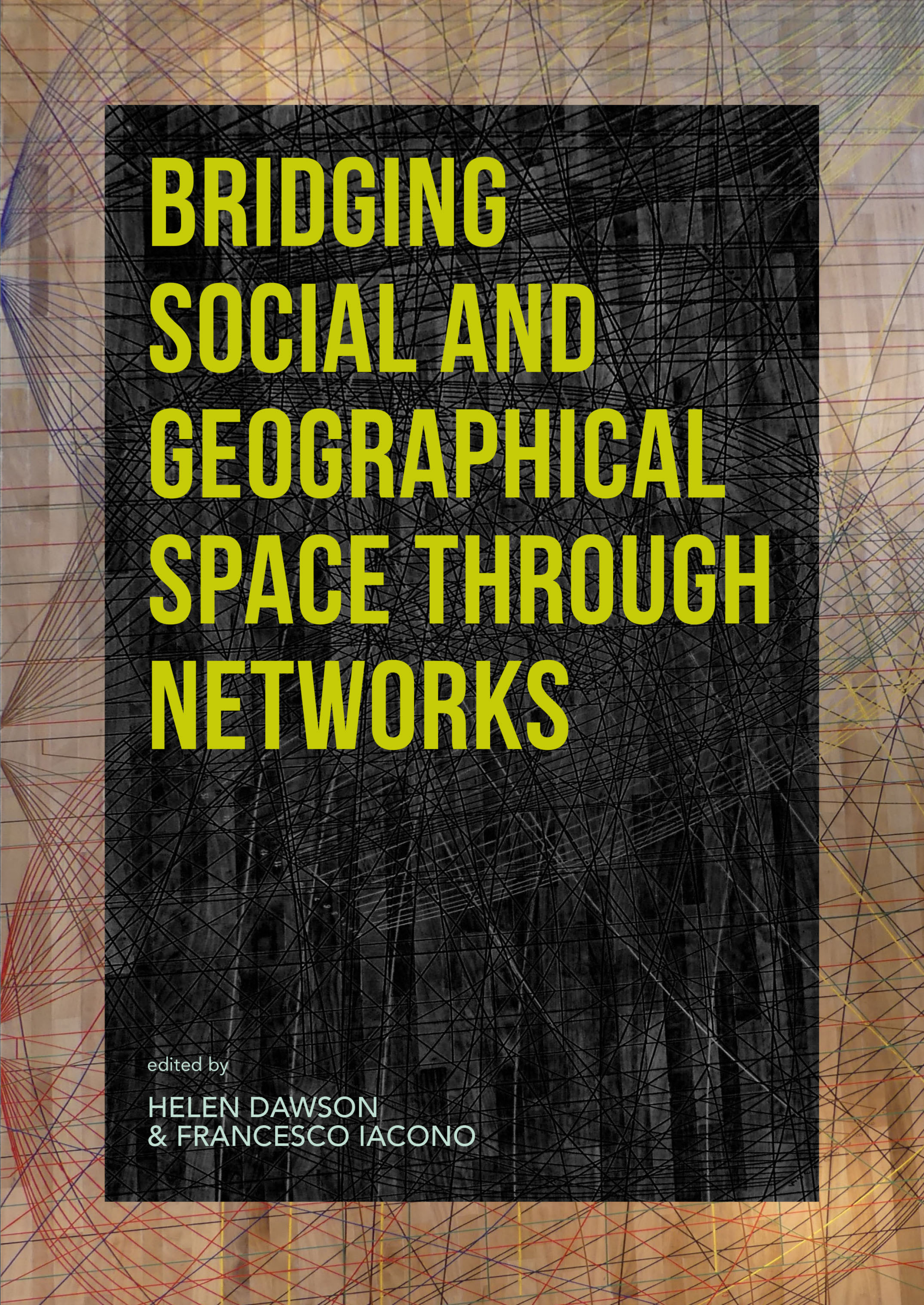

# BRIDGING SOCIAL AND GEOGRAPHICAL SPACE THROUGH NETWORKS

edited by

HELEN DAWSON
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# Contents

# Terrestrial Transportation Networks and Power Balance in Etruria and Latium Vetus between the beginning of the Early Iron Age and the end of the Archaic Period

Francesca Fulminante, Alessandro Guidi, Sergi Lozano, Ignacio Morer, Luce Prignano

*Terrestrial transportation networks, modelling, central Italy, Iron Age urbanisation*

## Introduction

In the last ten years, increasing attention has been devoted to understanding settlement systems through the application of Central Place Theory, locational models, Proximal Point Analysis, as well as gravitation and other interaction models (see for example, Fulminante 2014 with reference to previous studies, or more recently Nakoinz 2013a, b, c, Bevan and Wilson 2013, Paliou and Bevan 2016, Evans et al. 2013, Evans and Rivers 2017, Palmisano 2017). Such studies usually focus on the relative importance of the sites and attempt to work out to what extent general factors (*e.g.*, topography or social-ecological advantages) can explain why some places become more prominent than others. The data they take as input are largely limited to size and position of settlements, frequently the most homogeneous data available to archaeologists.[1]

The issue of whether and how settlements located in a certain territory were organised at the regional level is considerably more difficult and can be regarded as mostly unresolved. Whilst the existence of a certain degree of regional organisation can be tackled by techniques for the analysis of site distributions such as nearest-neighbour

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[1] Today new approaches are also trying to include cultural factors in network approaches by using different types of material culture, which is partially more complex given the heterogeneity and fragmentary nature of archaeological research and data, but seems very promising (see *e.g.* Fulminante forthcoming and contributions in Donnelan 2020); and more specifically attempting to combine Central Place Theory with Network Analysis such as in the innovative approach by Nakoinz et al. 2020 with previous references.

in: Dawson, H. and Iacono, F. (eds) 2021. *Bridging Social and Geographical Space through Networks*. Leiden: Sidestone Press, pp. 31-46.

analysis (Pinder et al. 1979), that help distinguishing between randomly distributed and clustered (organized) settlements, more complex matters remain out of reach. To what extent did past communities cooperate or compete? Were they just struggling for their individual benefit or were they aware of their interdependence? These are just a few questions that can in principle be addressed quantitatively, but what kind of data is suitable for hypothesis selection when dealing with these issues?

In a recent work (Prignano et al. 2019), we propose to gain a better understanding about these important topics by analysing Terrestrial Transportation Infrastructures (TTI). Indeed, the system of roads that existed in a territory might encode the footprint of processes and interactions at the regional scale. Starting from the Bronze Age, but even more with the advent of the Iron Age, the increasing social complexity and the accumulation of resources set the conditions for humans to have both the incentive and the capability to build roads (Lay 1992, Earle 2011(1991)). Constructed roads flourished along with the development of urban societies, when performing cuts, building bridges, or removing obstacles became both necessary and affordable.

The importance of TTI for the understanding of the political and social organisation of the communities that created and maintained them has been previously assessed, for example in relation to the Roman Empire (*e.g.,* Chevallier 1976, Taylor 1979, Crumley and Marquadt 1987, Purcell 1990, Mattingly 1997. In the 1990's Trombold presented an important collection of works on TTI in the New World (Trombold 2011 (1991), followed by Jenkins 2001 and Smith 2005). Recently, a renewed interest in TTI seems to have produced a number of new studies in Pre-Roman and Roman Europe (*e.g.,* Nakoinz 2012a, b; Faupel 2018; Faupel and Nakoinz 2018; Filet 2017; Groenhuijzen and Verhagen 2016; Verhagen et al. 2019), suggesting that this is a growing field of research (see *e.g.* recent projects such as ORBIS[2] by Stanford University, or the New Transhumance project in Toscana, Pizziolo et al. 2016).

Building on this literature, we propose to take a further step and try to infer aspects of the political organisation of a region from the quantitative analysis of TTI. In particular, we will focus on roads that connected human communities with each other, since their function was directly related with inter-settlement interactions (between villages, towns, and cities), and it is hence sensible to assume that they were the output of a collective effort for the benefit of one or more of the parties involved. More specifically, we developed a baseline methodology to contrast hypotheses about the organisation of a system of settlements, starting from a regional road map. Such a methodology consists of three fundamental ingredients: 1) a procedure for extracting relevant quantitative data from road maps; 2) a set of competing hypotheses about organisational aspects of road construction; and 3) formal models translating such hypotheses into mechanisms for generating synthetic data to be compared against the empirical ones. The underlying idea is that some models reproduce relevant features of the empirical TTI with higher accuracy than others. Thus, we can determine which hypothesis (or hypotheses) better explains the empirical evidence and is therefore more likely to resemble the actual mechanisms of organisation. To develop such a methodology, we adopted network science as a general framework. We regard this as a natural choice, given that we chose to focus on road networks because of the information embedded in their connectivity and functionality.

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[2] See http://orbis.stanford.edu/orbis2012.

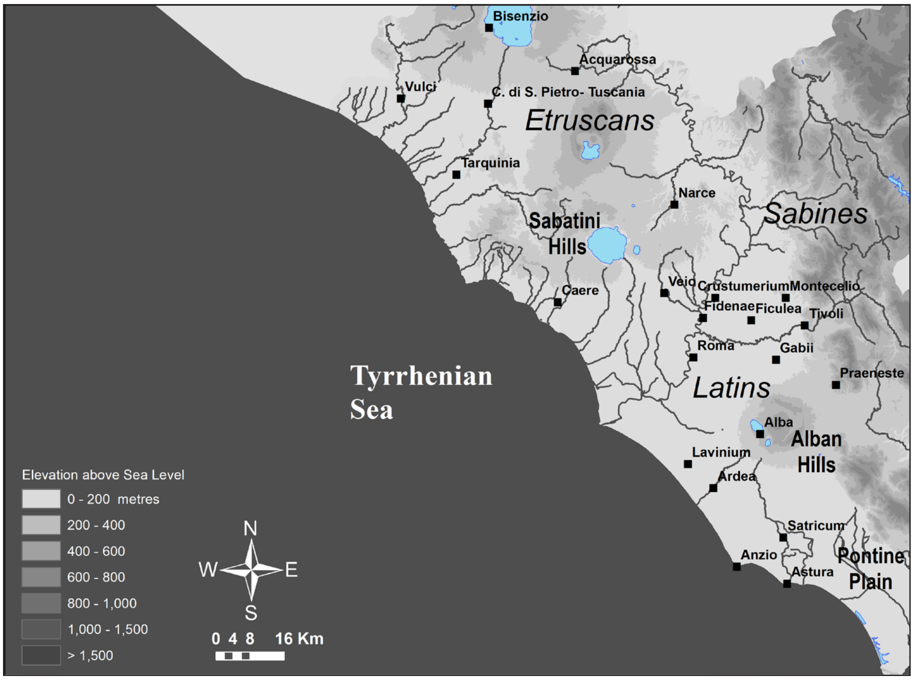

Figure 1: Southern Etruria and Latium vetus in Central Italy.

Network science provides us both an analytical toolbox for the characterisation of such aspects of TTI and a conceptual framework for model building (Prignano et al. 2019).

Here, we summarise and compare the results obtained for two different but related case studies: Iron Age Southern Etruria, a paradigmatic case we used for testing our technique (Prignano et al. 2019), and coeval neighbouring Latium vetus (Fulminante et al. 2017) (Figure 1). Both Southern Etruria and Latium vetus are very well-studied contexts, with detailed archaeological information about settlement patterns and an established tradition of studies on TTI. Obviously TTI are more archaeologically visible in later phases, during the Roman Era and partially in the Etruscan period, when road cuts and stone build roads start to appear. However, as we will show in the methodology section, Iron Age and Orientalising period routes have also been reconstructed (and traced on maps) based on direct (settlements position and alignments) and indirect evidence (existence of later roads on the same route). There is a wide degree of consensus among scholars on the trajectory especially of main routes connecting primary larger settlements.

Between the beginning of the Iron Age and the Archaic Period, (southern) Etruria underwent a complex process of urbanisation (see *e.g.* Stoddart and Spivey 1990, Barker and Rasmussen 1998, Rasmussen 2005, Bonghi Jovino 2005, Pacciarelli 2001, 2010, 2017, Riva 2010, Marino 2015, Stoddart 2016, Stoddart 2020). It was dominated by a number of equally ranked proto-urban centres that went on to develop into the city-states of the Orientalising and Archaic Period (Veii, Tarquinia, Caere, Vulci, Orvieto, and now also Bisenzio) characterised by a strong common identity but also by distinctive local “flavours” (Bietti Sestieri 2010). None of these centres were able to prevail over the others and impose on them a guiding role (Guidi 1985). Therefore, it has been suggested that at this time Etruria was characterised by an overall balanced dynamics of power (Fulminante and Stoddart 2012 and Stoddart et al. 2020).

Latium vetus was also organised in proto-urban centres and later city-states with a common material culture (Latial culture I-IV), similar burial costumes and a similar socio-political organisation (see *e.g.* Smith 1996, Smith 2007, Carafa 2014, Fulminante 2014, 2018 and Mogetta 2014). These polities were characterised by cooperative/competitive behaviours according to the model of the peer-polity interactions (Renfrew 1986, Verhagen 2015). However, in this region the power was quite unbalanced. In particular, it seems undeniable that around 950/900 BC, with the shift of the funerary areas from the Forum to the Esquiline and Quirinal Hill, Rome became by far the largest settlement in the region and lately emerged as a centralised authority with a noticeable disruption in the balance between the city-states (already Guidi 1982 and more recently Carandini 1997, Alessandri 2007, 2013 and Fulminante 2014).

In this paper, we compare the TTI of the two regions, Etruria and Latium vetus, in order to highlight similarities and differences that characterise these two different complex systems, and better understand how the two systems actually worked and whether similarities or differences in the TTI reflect different socio-political systems or at least different balance of power and interaction patterns within similar socio-political systems.

## Methodology

Our purpose is to infer how settlements were organised at the regional level by analysing the structure formed by the roads that connected them. The basic idea is to compare different hypotheses and quantitatively assess which of them is (or are) more plausible and, as stated above, we do this in three steps. Adopting a network science approach implies that the first step we have to take is to translate available information on pathways from the usual map format into networks, *i.e.*, mathematical structures made up of interconnected objects. Once the empirical system is mapped onto weighted geographical networks, one can apply the established analytic tools provided by network science for their characterisation.

However, such a methodology cannot consist of a mere analysis of network properties: we need to link the observed properties to the mechanisms that generated them. The final output of the application of the proposed technique consists of statements of the type “since we made an observation *X*, then process *Y* is more likely to have occurred than process *Z*”. Therefore, as a second step, we had to hypothesise generative mechanisms that might have created the empirical network and to contrast their different outcomes (synthetic networks) against the empirical evidence. More concretely, we devised competing network models, each one corresponding to a strategy according to which the nodes made decisions about which links had to be established.

The third and last step is the validation of the proposed models. We tested whether the synthetic networks that they generated were able of reproducing structural features of the empirical networks with satisfactory accuracy. If there existed at least one among them whose output resembled closely enough the empirical observations, then we could conclude that its underlying mechanism shared some similarities with the actual processes that generated the TTI under study. In the following subsections, we describe in more details each one of the methodological steps.

### *Construction of the empirical networks*

For this study, we considered all known Southern Etruria and Latium vetus settlements between the beginning of the Early Iron Age and the end of the Archaic Period that are larger than 1 ha. A dataset of Latium vetus settlements had already been collected and analysed in another work by one of the authors (Fulminante 2014). The useful works on the same region by Luca Alessandri have also been consulted (Alessandri 2013, 2016). For Southern Etruria, our main references were the *Repertorio dei Siti Preistorici e Protostorici della Regione Lazio* (Belardelli *et al.* 2007), the *Dictionary of the Etruscans* (Stoddart 2009) and the work by Marco Rendeli on the territorial organization of Southern Etruria in the Orientalising and Archaic Period (Rendeli 1993). In addition, the list of settlements was updated on the basis of more recent publications in *Studi Etruschi*, and the most important conference proceedings (*e.g. Preistoria e Protostoria in Etruria, gli Annali della Fondazione per il Museo "C. Faina"*), as well as exhibition catalogues (*e.g.* Della Fina and Pellegrini 2013).

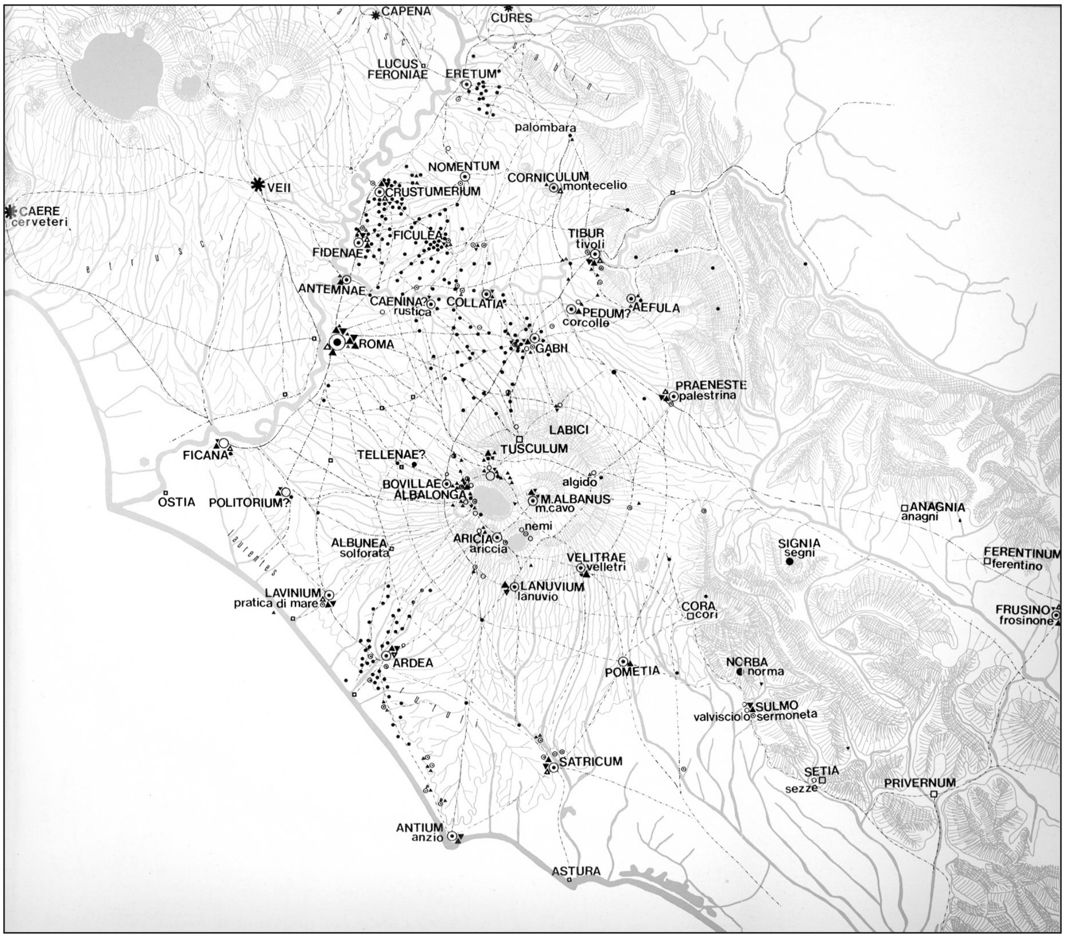

Figure 2: Latium Vetus terrestrial communication and transportation routes during the Archaic Period according to Lorenzo and Stefania Quilici Gigli (from Colonna 1976).

As mentioned in the introduction, prehistoric and proto-historic routes are less visible archaeologically because of their characteristics, being mainly track and used routes rather than monumental stone constructions. However, in the Italian archaeological and topographic tradition many scholars have tried to reconstruct these routes on the basis of the following principles: 1) topography of the region, 2) the position of settlements (and/or sanctuaries and funerary monuments) attested archaeologically (direct evidence) and 3) the remains of monumental roads of the later periods (inference on the base of later evidence). Therefore, there is a relatively established tradition of study which has reached a good consensus among scholars. For Latium vetus we used the reconstruction by Lorenzo and Stefania Quilici Gigli (in Colonna 1976) elaborated in a map at the regional level for the Archaic Period (Figure 2).

For the Etruscan region, unfortunately, a comprehensive study is still missing (but see Tuppi 2014). Therefore, we considered several works, whose authors also suggested reconstructed routes on maps (Potter 1979, 1985, Zifferero 1995, Tartara 1999, Brocato 2000, Enei 2001, Bonghi Jovino 2008, Schiappelli 2008). To test these suggested routes, we verified their alignment with settlements discovered more recently, after the publication of those works, and observed that they were generally coherent with those routes, so we are confident of the reliability of those reconstructions.

The task of translating road maps into networks is not straightforward and can be performed in many alternative, not equivalent ways. Since we are studying inter-settlement interactions, we need our nodes to be human communities with a certain degree of political agency, such that they could play an active role in shaping the regional infrastructure. Then, the simplest option for defining edges is to consider that a bidirectional link between two sites is established whenever they are directly connected by a terrestrial route, with no other settlement in between. Once the rules are set, the second stage consists in selecting and organising the empirical data.

By considering the maximum period in which the settlements co-existed without major changes, we obtained five time slices:

- Early Iron Age 1 Early (EIA1E): (950/925- 900 BC)
- Early Iron Age 1 Late (EIA1L): (900- 850/825 BC)
- Early Iron Age 2 (EIA2): (850/825- 730/720 BC)
- Orientalising Age (OA): (730/720- 580 BC)
- Archaic Period (AA): (580-500 BC)

Both settlements and communication routes have been considered as unchanging within each time slice. In this sense, the analysis considered five static networks rather than a system in evolution. Finally, since we were interested in terrestrial routes as the product of a collective effort, requiring the allocation of resources to be built and maintained, it was essential to somehow quantify their cost. It is reasonable to assume that, beyond the peculiarities of road building in each individual case, the cost of a road is roughly proportional to its length. To determine the length associated with each connection, we could have implemented GIS based analysis, measuring it directly in the case of known ways and adopting a least-cost path (LCP) approach for those paths whose route is not completely known. However, using such different levels of precision for different links might be detrimental. We concluded that the optimal way to address the geographical factor was to represent sites as geo-localised nodes and assign weights to the links according to the geodesic distance between the nodes they connect. This is a quite good approximation provided that the region is limited and presents a relatively homogeneous landscape, but more importantly, the lack of precision is evenly distributed among the nodes, without biases towards less studied areas (for a more exhaustive discussion of the benefits and issues of the available alternatives, see Prignano et al. 2019, Sec. 3.1).

As a final note, we have to acknowledge that we did not take into consideration either connections with settlements that do not belong to the regions under study or those that joined places on the two sides of the limit between the Latium vetus end Etruria. Since we analysed interactions between polities within the same regional system, and our focus is on the global scale, not on the properties of individual settlements, this is not a central issue for the present work. Nonetheless, we are aware that disregarding such links may affect some aspects of our results and we are currently investigating the importance of inter-regional connections in a new study that looks at the two regions as interdependent systems.

### *Characterisation of terrestrial route networks*

We are interested in characterising TTIs by means of particular features that conditioned the way they functioned and determined their performance, i.e., the efficiency and robustness of the communication that took place on it. Such systemic features are not defined by individual connections between specific pairs of settlements but by all of them. For instance, we might focus overly on the presence of a few central places that are much better connected than many peripheral ones (inequality) or on the existence of routes or settlements that, if inaccessible, made the network fall apart (fragility). Hence, we selected and calculated five network metrics that translate in quantitative terms some relevant features of the TTI of Etruria and Latium vetus from the beginning of the Early Iron Age to the end of the Archaic Period. In other words, these indicators were chosen in such a way that two networks with similar values in all their measures are expected to perform similarly in terms of transportations and communication processes (Albert and Barabási 2002, Boccaletti et al. 2006).

The selected network measures are: 1) average node strength (also known as average weighted degree) $<s_i>$; 2) average edge length $<l>$; 3) average clustering coefficient $<C>$; 4) global efficiency $<E_{glob}>$; 5) local efficiency $<E_{loc}>$. These measures are explained in detail in a recent publication by the authors (Prignano et al. 2019). The first three measures are very common in network analysis and represent respectively: the mean total length of the links adjacent to a node; the mean of the weights (length) of all links present in the system; the presence of closed triangles in the network. The last two, however, are less common and specific of geographical network analysis.

In particular, the concept of efficiency can be applied to networks both at the local and global scale. The efficiency of communication between two sites is defined by the length of the shortest path (on the network) between them divided by the linear distance between their location: the longer the path between two nodes in comparison with their distance, the less efficient the network. The global efficiency is calculated as an average on all pairs of nodes.

The local efficiency measures the capacity of the network to react to a crisis at the local level. More concretely, the local efficiency of a node defines how efficiently information is shared and moved among neighbours if that node is eliminated. The overal value is obtained by averaging over all the nodes (Vragović et al. 2005).

### *Principles of network modelling*

In order to gain a better understanding of how settlements were organised at the regional level, we analyse the structures formed by the roads that connected them searching for the mechanisms underlying the decision-making processes that created them. To this aim, we produced models able to generate "synthetic networks" from different hypothetical mechanisms and compared such networks with their empirical counterparts obtained as explained above, for each age and region.

The idea of network models as a means for explaining some features of real networked systems dates back to the late 1990s and builds up on a long tradition developed in the framework of mathematical sociology during the previous decades. Initially, the three most studied properties of social networks – and later on of other types of systems, such as citation networks, airport networks, or the world wide web, among many others – were the degree distribution (how many nodes have how many links), the clustering coefficient, and the average path length (the average number of steps along the shortest paths for all possible pairs of network nodes). A large part of empirical networks have heterogeneous degree distribution, high clustering coefficient, and very short path length (resulting in the famous "six degrees of separation"). Already in the 1970s, it was clear that this combination of features can neither be explained as the mere effect of chance nor can it be obtained by building connections according to simple mathematical rules. For instance, if we connect node pairs at random with a certain probability, by tuning such probability, we are able to reproduce the observed number of links of any empirical system, and the average path length is also likely to be close to the observed one. On the other hand, the degree distribution will be much more homogeneous and the clustering coefficient (related with number of triangles) significantly lower. Alternatively, it is straightforward to come up with a mathematical rule for connecting nodes such that the clustering coefficient is similar to the observed one, but then the average path length will be too large and the degree distribution still too homogeneous. Both random and regular networks reproduce some of the features of real networks, but they cannot display them altogether. This is the main motivation for the onset of network science: to answer the question of which mechanisms are able to generate the properties of real networks.[3]

Such mechanisms are implemented as algorithms that work in different fashions: in some cases, they take as a starting point a regular or random network and proceed to modify it by rewiring or adding connections; in some other cases, nodes are also added at each step. One of the most paradigmatic network models is the Barabási-Albert (BA) model (Albert and Barabási 2002), an algorithm that adds nodes one at a time. Each new node establishes a connection with any of the existing ones with a probability proportional to the links that the latter already has. In other words, the new nodes have a "preference" to attach themselves to the already heavily linked nodes. Thus, heavily linked nodes ("hubs") tend to quickly accumulate even more links, while those with only a few links are unlikely to be chosen as the destination for a new link. The BA algorithm simulates a system that experiences the well-known "the rich get richer" effect, and the resulting synthetic networks display a highly heterogeneous degree distribution. In more concrete terms, we

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[3] It is usual for network scientists to refer to the networks built on the bases of empirical observations as "real networks" to differentiate them from "artificial" or "model generated" graphs. However, in the context of archaeological studies, we preferred the term "empirical networks".

can imagine that each node is, for instance, a scholarly paper, while the links stand for citations. Although the actual criteria for selecting references are far more complicated than the mechanism implemented by the model – no one picks papers at random according to a certain probability – the BA algorithm captures a general trend (highly cited papers are more likely to be cited even more) and is able to reproduce a distinctive feature of real citation networks. In this way, the hypothesis that authors when building a list of references for a new publication tend to have a preference towards already popular papers, can be corroborated (even though it is not definitively proven, since it is still possible that another model implementing a different mechanism reproduces the same trait). Citation networks are not the only type of system that can be (partially) explained by the BA algorithm, which was originally devised as a network model for the Web. Its importance does not lie in its ability to perfectly reproduce some phenomena, but in the capability of capturing something general that is common to a wide range of systems. The same algorithm can be interpreted in many ways according to different contexts (nodes may be papers, websites, airports, hence links are citation, hyperlinks, flights, etc.), while the underlying mechanism stays unchanged. This is, roughly speaking, how network modelling works: an abstract mechanism (*e.g.*, the rich get richer) is translated into a generative algorithm for networks (*e.g.*, preferential attachment), but in order for the model to explain something specific of the system under study, we need an interpretative metaphor (*e.g.*, highly cited papers have greater visibility).

### *Network models for TTIs*

In our work, each network model implements an algorithm that, starting from a certain number of disconnected sites (the settlements of the empirical networks), decides what links should be added to build up the artificial networks. The approach is similar to the BA model, but in this case the nodes are not characterised by the “timestamp” of their creation but rather by their geographical coordinates. They all exist in the initial state, while the links are created one at a time.

Since our goal was to unveil the basic principles governing the interaction between the different communities of a regional system, we had to consider a limited number of radically dissimilar scenarios. In the first one, settlements did not have information about the TTI at the regional scale, neither did they share any common interest; in the second one, they did have information at the regional scale, but shared no common interest; in the third and last one, they had both regional scale information and common interests. In all these cases, we made the general assumption that any settlement needed to be well connected, that is, they all actively tried to get as many links as possible. More specifically, we assumed that each settlement pursued being able to reach any other through a path as short as possible. The difference between the three scenarios lies in their means and criteria for setting priorities.

Once the basic assumptions were set, we proceeded to translate them into algorithms for establishing links between nodes. This step implies a certain degree of lack of determination since it can be performed in multiple ways. Simplicity was the guiding principle that shaped our models. Refinements are always possible afterwards, but the baseline needs to be directly connected with the main concept one wants to test, otherwise the interpretation of the result becomes more difficult and potentially ambiguous. Hence, we designed a minimalistic set up in which each node, at each step, had a preference about which link had to be built, and it was always a link connecting itself to another node which it considered to be the most beneficial for its connectivity. Such individual (local) preferences were sorted in different ways, depending on whether the settlements were interested in building a functional TTI at the regional scale (third scenario) or not (first and second scenarios). If they were interested only in their own connectivity, every settlement tried to establish its preferred link as the next step; otherwise, it tried to reach some kind of agreement with its neighbours and their individual preferences were sorted out according to a shared criterion. At the same time, the way they set their preferences depends on the information available to them.

After defining the abstract principles, we needed to translate them in terms of rules for establishing links, thus devising a set of generative network models.

For the sake of simplicity, we made the additional assumption that all node-settlements were intrinsically equally important. In other words, we did not make any supposition about their power, richness or attractiveness: our models take as an input no other node attribute beside the geographical position. In this way, the node-settlements based their choice on geographical (distances) and topological (already existing links) information only. In the first scenario, their knowledge was limited to the links that connected them to other nodes, while in the second and third ones, nodes knew any existing path joining them to any other place independently on the number of steps (intermediate nodes). Hence, in the first case, at each step, each node's preference was to build a new link with the closest node that was not already connected to it. On the contrary, in the case they had complete topological information (second and third scenarios), since their goal was to improve their connectivity, they would have preferred to compare the length of any existing path connecting them to any other node with the length of the corresponding direct link, to better assess the benefit of building it. In quantitative terms, the most beneficial link would be the one that minimises the ratio of its length to the length of the shortest existing path to the same node (best "shortcut").

Finally, we implemented the interplay between the individual node-settlement interests. If it was pure competition, then at each step every node tried to prevail over the rest and build its preferred link. A realistic simulation of such processes, besides being extremely difficult, would have not fit in with the minimalistic approach of network modelling. More importantly, it was not necessary. We took a step back and assumed that the output of the competitive interactions between node-settlements was indeterminate. Each node had the chance to prevail at each step, according to a certain probability distribution, but we did not know a priori which one was going to build a new link at the next step. Therefore, the corresponding network models (first and second scenarios) were not deterministic. If we ran them several times, they generated several different networks -similarly to what happens with the BA model- and their outputs had to be analysed statistically. To avoid making arbitrary assumptions, at this stage, we decided that the probability distribution had to be uniform, that is, each node had the same chance to prevail at each step.

The third scenario presents a radically different situation. Since in this case the nodes were supposed to reach an agreement and decide collectively which link had to be built at each step, we had to set a criterion for doing so. The settlements would have compared their individual preferences and settled for the most beneficial at the regional scale. This process could have been easily implemented as the optimisation of some function and there were various plausible options that we could have adopted. Once more, seeking simplicity, we chose not to introduce a new ingredient. Individual preferences were already set according to a quantitative criterion and that same criterion could be exploited to compare them. Thus, at each step, the model built the shortcut that was the most beneficial of all, shortening paths at the regional scale.

Summarising, in the first model, called the L-L (local-local) model, node-settlements pursued their local interests relying, for their decision making, on local information. At each step, a node was extracted at random and a new link was built, connecting it to the closest one among the nodes not already connected to it. The second model, which we named the G-L (global-local) model, shared with the L-L model the fact that node-settlements pursued their local interests, but they did so basing their preferences on global (system-scale) topological and geographical information. At each step, a node was extracted at random and, among all the possible links connecting it to any other node, the one that minimised the ratio of its length to the length of the already existing shortest path will be established. Both the L-L and the G-L models are not deterministic and each run produces, in principle, a different network. In the third and last baseline model, the nodes had global information as in the G-L model, but pursued a regional scale benefit, mediating between their local preferences. At each step, the algorithm built the link associated with the (globally) minimal value of the ratio of the geodesic distance between two disconnected nodes to the length of the already existing shortest path joining them. This model is deterministic and will always generate the same network for a given set of input parameters. We named it the equitable efficiency (EE) model because of the effect of the algorithm on the global efficiency of the networks that it generates.

Besides the three baseline models, we devised a fourth one by introducing a simple modification to the EE model, thus including a version of "preferential attachment" (model EE-pa) that, in this case, was integrated in the framework of a deterministic algorithm. Without entering into technical details, the main idea was that, while in the original model all the settlements were on the same ground and the links to be built were selected among the individual preferences according to an objective and fair criterion, in the modified version the preference of nodes with more and larger links were entitled to a higher priority level. In this way, nodes with greater strength (total length of its adjacent links) tended to gather even more.

To complete the definition of the models, there was one more rule that needed to be set. It was necessary to establish a stopping condition for the creation of new links. Since the aim was to compare the networks generated by the models with the empirical ones, we considered that it was appropriate to equate their total link length. The algorithms take as input the positions of the settlements and build links between them until the total length of the connections that have been established is equal to that of all the connections in the corresponding empirical network (for an exhaustive discussion of the motivations and implications of this choice, check the previous publication by the authors, Prignano et al. 2019).

## Discussion and results

### *Assessment of the network models*

To assess whether any of the proposed generative mechanisms was likely to have shaped southern Etruria and Latium vetus TTIs, we compared model generated networks with their empirical counterparts, for each age and region. We performed such a comparison considering the network metrics that we proposed for the characterisation of terrestrial

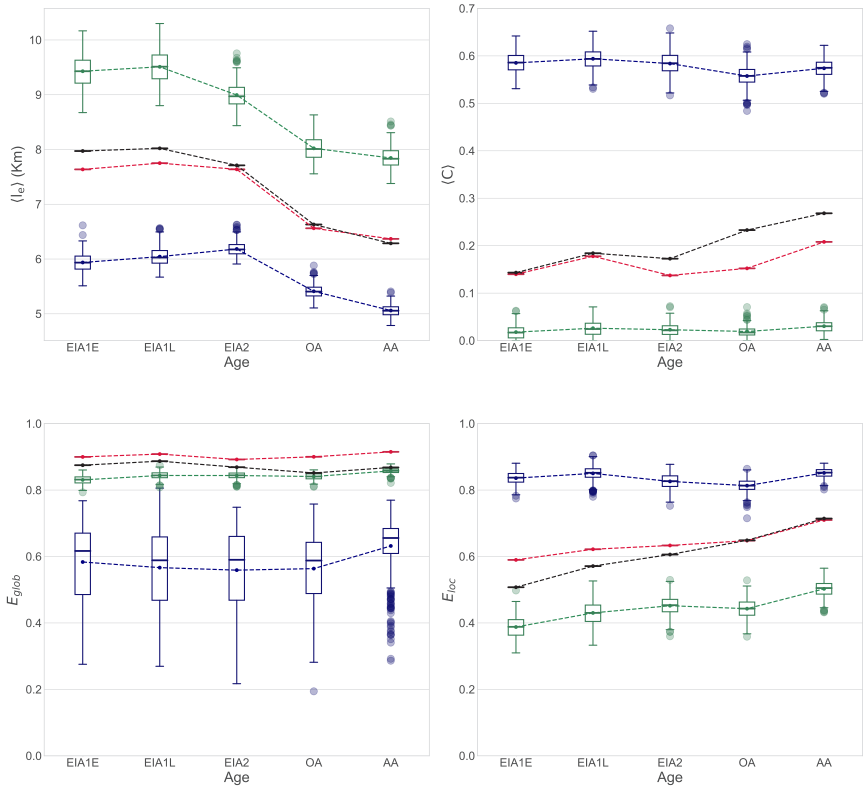

Figure 3: Etruria: comparison of the results of the calculation of characterizing measures for the empirical network and those produced by the models (black = empirical network, blue = model L-L, green = model G-L; red = model EE).

route networks. Here, we summarise the most relevant results, while a technical discussion of quantitative aspects can be found in Prignano et al. (2019) and Fulminante et al. (2017) for southern Etruria and Latium vetus, respectively.

Concerning southern Etruria, the first two models captured some of the characteristics of the empirical networks but missed some others. Specifically, the L-L model overestimated the clustering coefficient and the local efficiency and underestimated the average edge length and the global efficiency. On the other hand, the G-L model underestimated the clustering coefficient and overestimated the average edge length but is an almost perfect match for the global efficiency. On the contrary, the EE model reproduced with good accuracy all the relevant features of the empirical networks for all periods considered, with the only exception of a non-negligible difference in the clustering coefficient for the last three periods (Figure 3).

Differently from Etruria, in Latium vetus each model reproduced some of the trends of the figures of the empirical networks but always missed some others (Figure 4). In particular, the L-L model did not reproduce any of the trends of the empirical network (except for the global efficiency in two particular periods, namely EIA2 and OA). The G-L model reproduced quite well the average edge length, the local and global efficiency, but underestimated the clustering coefficient. Model EE reproduced quite well the clustering coefficient and the global efficiency (very similar to the G-L model) but underestimated the average edge length and overestimated the local efficiency. Furthermore, in the empirical networks, the heterogeneity of the node strength (measured as its standard deviation) was greater than in any model generated counterpart. Adding a tuneable preferential attachment mechanism to the EE model (model EE-pa) enabled us to generate topologies that resembled the empirical ones more accurately, although not as accurately as the EE model did in the case of Southern Etruria.

### *Interpreting the quantitative results*

The proposed network science approach allowed us to hypothesise basic mechanisms that could have governed the decision-making process that shaped the terrestrial route network of the two regions under study.

Our conclusion is that in likelihood all the actors involved (cities and villages) were trying to build TTIs such that it was possible to reach every place from any place through a fairly short path, not permitting the existence of poorly connected areas, which could have damaged the functioning of the settlement system (in terms of commerce, communication, and defence) at the regional scale. replace with additional text:

It is interesting to note that in a least-cost path network classification proposed by Waugh (2000), this type of network, defined ‘least-cost-path to the builder’, is typical of agrarian societies, where arable land is precious, or scarcely populated regions, where creating routes is too expensive. This type of network contrasts the so called ‘network to the user’, which connects in the quickest way each possible pair of the system and is typical of hunter-gatherer societies (Fulminante 2012). Both Latium and Etruria are definitively agrarian societies growing in complexity and probably Etruria is slightly less densely populated than Latium. A third type of network, compromising between the two above, is the ‘least cost triangulation network’, in which the least-cost is applied only to nearest sites, implying that connections to close sites are more important than distant ones. Interestingly we applied the Delaunay model triangulation to build Latin networks in an earlier work, and they performed rather well in term of correlation between centrality indexes and centres predicted to be important by their size (Herzog 2013). A drawback of all these models is that they assume equal rank and contemporaneous sites. We will go back to these classifications in further work on least-cost paths networks.

However, it is important here to note that while in southern Etruria, optimizing the communication in the region, seemed to be the only preoccupation of all the cities and villages, regardless their status, in Latium vetus those who had been initially favoured by their location, appeared to exploit such condition pursuing local ambitions for an even better connectivity. Nonetheless, this distinguishing element did not disrupt excessively the balance at the regional scale. Latium vetus still had a very efficient terrestrial transportation infrastructure, despite that few sites were characterised by a greater number of connections.

Latin settlements could probably afford building more heterogeneous (less equitable) TTIs thanks to the relatively large total link length of their network, which allowed them to limit the damage of a non-optimal geographical distribution of paths. It is indeed worth noticing that, even though the total link length is generally larger in Southern Etruria than Latium vetus, if properly compared – taking into account the number of nodes and their average distance (Morer et al. 2020, table 1) – the latter turns out to be considerably better connected. Consequently, implementing a rich-get-richer mechanism would have been critical for the Etruscan. We cannot say whether the equitable nature of the interactions between Etruscan

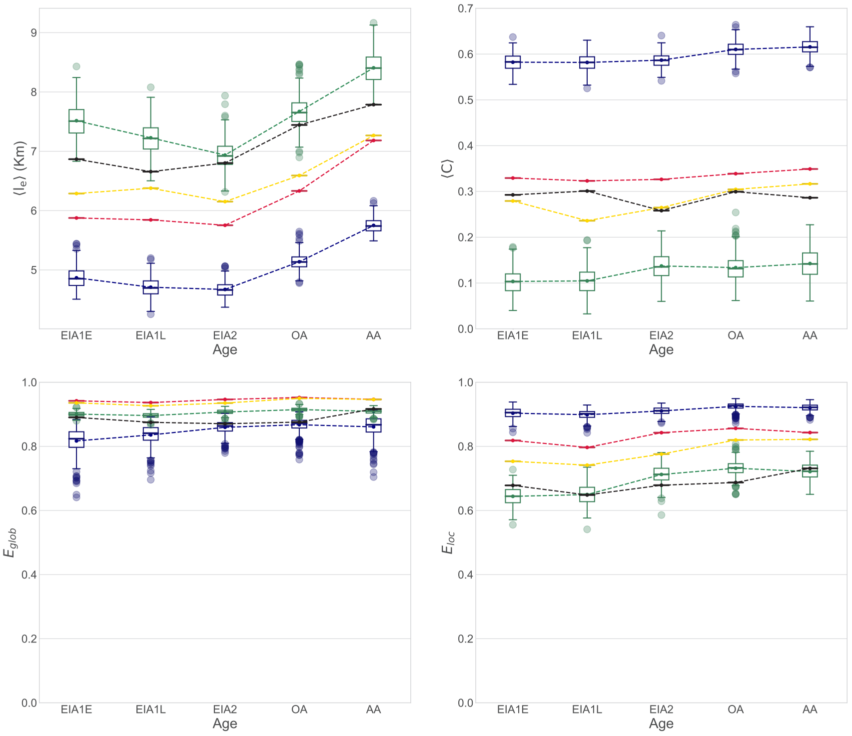

Figure 4: Latium vetus: comparison of the results of the calculation of characterising measures for the empirical network and those produced by the models (black = empirical network, blue = model L-L, green = model G-L; red = model EE; yellow = model EE-pa).

cities made their resources scarcer (both in terms of settlement density and roads) or instead it was the other way around, uncovering this kind of causal relations is beyond the scope of our methodology. Nonetheless, our results suggest that a compact and highly connected region as Latium vetus could sustain unbalanced powers, while for Southern Etruria -a bigger and less densely populated region- power balance looked almost as the only option.

On closer inspection, we found hints that the introduction of preferential attachment as a refinement mechanism to the EE model could explain the emergence of Rome as a prominent site (see Figure 5). According to the EE-pa model, some sites, favoured by a convenient geographical position (in relation to the rest of the sites), were able (and willing) to leverage this initial advantage to increase their influence and gather even more power.

In the case of Rome, which had the greatest node strength in the empirical networks, the site happened to be also favoured by the algorithm. However, in the case of other heavily connected cities -such as Gabi- the model failed to explain their strength. At the same time, the algorithm bestowed higher strength to other sites, as for instance Satricum or the considerably less important site of Guadagnolo.[4]

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[4] It ought to be noted here that Gabii is another primary and very important site in Latium vetus that shows clearly some specular characteristics as it will be shown in an ego-network approach that will be presented elsewhere (Fulminante et al. forthcoming); Satricum is also rather important but located in a more peripheral position; while only some sporadic Iron Age materials are known from Guadagnolo.

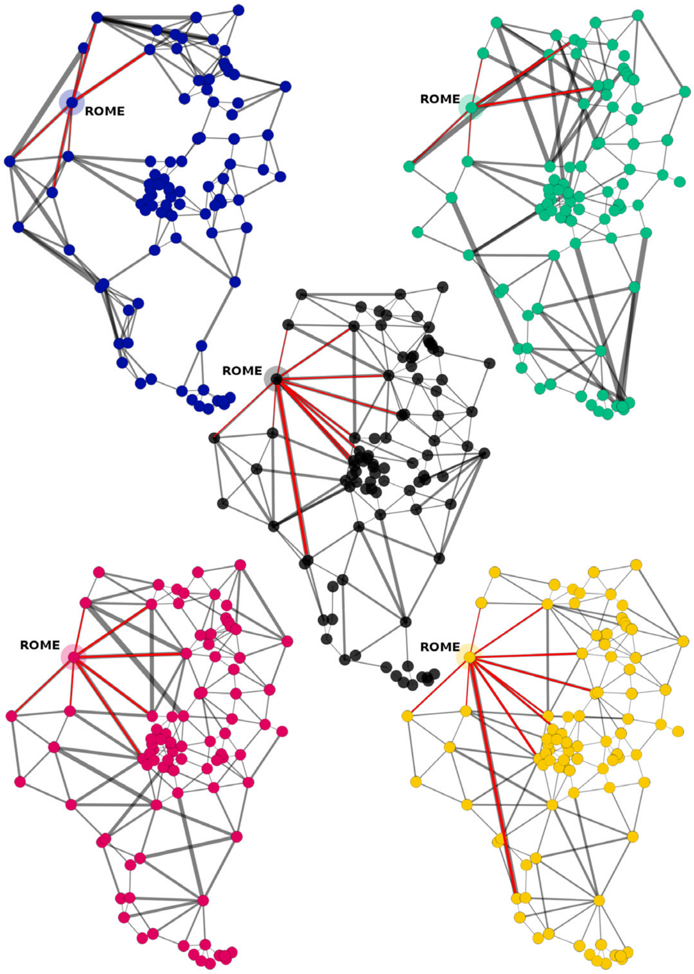

Figure 5: Latium vetus: empirical network (black) and networks produced by the models (blue = L-L, green = G-L; red = model EE; yellow = model EE-pa).

The EE-pa model reproduced a specific feature presented by Latium vetus TTI that neither the G-L model nor model EE could reproduce, that is, the existence of few sites with many distant links (Figure 5), but we did not expect it to identify who prevailed over whom or to reproduce correctly the local scale, since there were too many factors that could have determined what happened at the level of individual settlements (factors that were not included in the algorithms). Nevertheless, the apparent emergence of Rome as the most important hub of model generated networks, hints at the crucial role played by its geographical position within the system of settlements, the only attribute that the algorithm takes as an input.

The case of southern Etruria was different: there was nothing this remarkable at the local scale. Not only was the empirical node strength distribution less skewed, but the network metric itself seemed also to be almost unrelated with importance of the corresponding sites, that is, it showed lower correlation with the settlements' size (Guidi et al. forthcoming). In this case, the association between strength and power was weak, a fact that was consistent with the capacity of the EE model of reproducing the most important feature of the empirical network accurately assuming that all the nodes stood on the same ground (no preferential attachment), not considering which ones had been favoured by their position in the first steps of the algorithms. That is, possible initial advantages in terms of connectivity did not represent, in southern Etruria, a source of power imbalance and, in general, being better connected did not imply being more important.

## Conclusions

In this paper we addressed the intriguing issue of the regional organisation of settlement systems through the structural analysis of their Terrestrial Transportation Infrastructures (TTI). Specifically, we proposed a methodology to contrast different hypotheses linking regional organisation of settlement systems and mechanisms shaping road network design.

To validate this novel quantitative approach, we applied it to compare two well-known neighbouring settlement systems: Southern Etruria and Latium vetus during the Iron Age. Such a comparison allowed us to highlight similarities and differences that characterise these two different complex systems, and better understand how the two systems worked. We could explore whether similarities or differences in their TTIs could reflect different socio-political systems (or, at least, different balance of power and interacting patterns within similar socio-political systems).

By means of this case study, we have shown how our proposed approach can be applied to compare different settlement systems and corroborate previously proposed hypotheses. Indeed, even though we could never be sure that we devised the best model for a given case study, it is possible to establish whether a given model works better in a certain region than in another one. Specifically, we cannot be sure that a "rich get richer" mechanism (even a weak one) did not shape Etruscan TTIs. However, we can conclude that there are higher chances that such a mechanism had an effect in shaping Latin TTIs. Generally speaking, if we have data that can be translated into networks, then generative algorithms are a good tool to understand the mechanisms that shaped those networks since they allow us to explore multiple scenarios playing the "what if?" game.

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