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Networks and the resilience and fall of empires

A macro-comparison of the Imperium Romanum and Imperial China[1]

With 24 figures and 6 tables

Introduction

In her 2009 book on *Law and Geography in European Empires*, Lauren Benton (2009, p. 2) stated: *"Empires did not cover space evenly but composed a fabric that was full of holes, stitched together out of pieces, a tangle of strings. Even in the most paradigmatic cases, an empire's spaces were politically fragmented; legally differentiated; and encased in irregular, porous, and sometimes undefined borders. Although empires did lay claim to vast stretches of territory, the nature of such claims was tempered by control that was exercised mainly over narrow bands, or corridors, and over enclaves and irregular zones around them."*

This observation on more 'cobwebby' spatial manifestations of imperial rule can be connected with earlier studies of *Monica L. Smith* (2005 and 2007), who borrowed concepts from ecology in order to characterize ancient states and empires as a *"series of nodes (population centres and resources) joined through corridors (roads, canals, rivers)"*. Along similar lines (but without reference to Smith), *Pekka Hämäläinen* wrote that what he calls the 'Comanche Empire' in the 18th–19th-century North American West *"rested not on sweeping territorial control but on a capacity to connect vital economic and ecological nodes—trade corridors, grassy river valleys, grain-producing peasant villages, tribute-paying colonial capitals"* (*Hämäläinen* 2013; *St. John* 2013). Moreover, even for modern-day polities and international systems, *Parag Khanna* (2016) has argued for replacing traditional cartographic approaches with a 'connectography' of routes, webs and corridors.

When referring to 'nodes' and 'connections', these authors (deliberately or unintentionally) use terminology from network theory; some, such as *Smith* (2005 and 2007) and others (*Glatz* 2009), have also argued for perceiving and depicting

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1 This contribution is based on a paper delivered at the 44th meeting of the Working Group for Research into Historical Landscapes in Central Europe (ARKUM e.V.) in Vienna on 20th–23rd September 2017.

empires as networks. Most, however, resort to verbal descriptions or graphic visualisations, at best, without applying the tools of actual network analysis, although there exist several such studies, dating back to the 1960s (*Carter* 1969; *Gorenflo* and *Bell* 1991).

In the following pages, we will demonstrate the potential to understand and model large-scale polities of the past as networks with a comparison of two 'paradigmatic' cases of imperial formations, the Roman Empire and Imperial China. Various recent volumes have been devoted to a comparison of diverse aspects of these two empires, which even had (infrequent and tentative) contacts which each other (*Mutschler* and *Mittag* 2008; *Scheidel* 2009; *Auyang* 2015). Network theory, however, provides a different and common analytical basis for comparison, beyond disciplinary boundaries. As will also become evident in the following pages, Rome and China clearly very much differed in the 'logics' of imperial connectivity, with the Imperium Romanum centred on a maritime Mediterranean core, while the sea marked more of a border for China with its web of terrestrial and riverine routes (*Mote* 1999; *Tuan* 2008; *Marks* 2017). Yet, both imperial formations under pre-modern technological conditions integrated enormous territories (of *c.* five million km^2 each, see *Ruffing* 2012, p. 32; *Auyang* 2015, pp. 4–5) and had a lasting effect on further developments in Western and Eastern Afro-Eurasia (*Preiser-Kapeller* 2018).

Some basic concepts and tools of network analysis

Network theory assumes *"not only that ties matter, but that they are organised in a significant way, that this or that (node) has an interesting position in terms of its ties"* (*Lemercier* 2012, p. 22). One central aim of network analysis is the identification of structures of relations, which emerge from the sum of interactions and connections between individuals, groups or sites and at the same time influence the scope of actions of everything and everyone entangled in such relations. For this purpose, data on the categories, intensity, frequency and dynamics of interactions and relations between entities of interest are systematically collected, allowing for further mathematical analysis. This information is organised in the form of matrices (with rows and columns) and graphs (with nodes [representing the elements to be connected] and edges [or links, representing the connections of interest]). Matrices and graphs are not only instruments of data collection and visualisation, but also the basis of further mathematical operations (*Wassermann* and *Faust* 1994, pp. 92–66; *Prell* 2012, pp. 9–16; *Barabási* 2016, pp. 42–67; for applications in archaeology and history: *Brughmans* 2012; *Knappett* 2013; *Collar, Coward, Brughmans* and *Mill* 2015; *Brughmans, Collar* and *Coward* 2016).

A quantifiable network model thus created allows for a structural analysis on three main levels (*Collar, Coward, Brughmans* and *Mill* 2015):

- The level of single nodes: respective measures take into account the immediate 'neighbourhood' of a node – such as 'degree', which measures the number of direct links of a node to other nodes (*Wassermann* and *Faust* 1994, pp. 178–183;

de Nooy, Mrvar and *Batagelj* 2005, pp. 63–65; *Newman* 2010, pp. 168–169; *Prell* 2012, pp. 96–99). 'Betweenness' measures the relative centrality of a node within the entire network due to its position on many or few possible paths between otherwise unconnected nodes. We interpret it as a potential for intermediation, while nodes with a high betweenness also provide cohesion and connectivity within the network (*Wassermann* and *Faust* 1994, pp. 188–192; *de Nooy, Mrvar* and *Batagelj* 2005, pp. 131–133; *Newman* 2010, pp. 185–193; *Prell* 2012, pp. 103–107). A further indicator of centrality is 'closeness', which measures the length of all paths between a node and all other nodes. The 'closer' a node is the lower is its total and average distance to all other nodes. Closeness can also be used as a measure of how much time it would take to spread resources or information from a node to all other nodes or how easily a node can be reached (and supplied with signals or material flows) from other nodes (*Wassermann* and *Faust* 1994, pp. 184–188; *Prell* 2012, pp. 107–109).

– The level of groups of nodes, especially the identification of 'clusters', meaning the existence of groups of nodes more densely connected among each other than to the rest of the network. A measure of the degree to which nodes in a graph tend to cluster together is the 'clustering coefficient' (with values between 0 and 1) (*Wassermann* and *Faust* 1994, pp. 254–257). In order to detect such clusters, an inspection of a visualisation of a network can already be quite helpful; common visualisation tools arrange nodes more closely connected (near) to each other ('spring embedder' algorithms) and thus provide a good impression of such structures (*Krempel* 2005; *Dorling* 2012). For exact identification, there exist various algorithms of 'group detection', which aim at an optimal 'partition' of the network (*de Nooy, Mrvar and Batagelj* 2005, pp. 66–77; *Newman* 2010, pp. 372–382; *Prell* 2012, pp. 151–161; *Kadushin* 2012, pp. 46–49).
– The level of the entire network: basic key figures are the number of nodes and links, the maximum distance between two nodes (expressed in the number of links necessary to find a path from one to the other; 'diameter') and the average distance (or path length) between two nodes. A low average path length among nodes together with a high clustering coefficient can be connected to the model of a 'small world network', in which most nodes are linked to each other via a relatively small number of edges (*de Nooy, Mrvar* and *Batagelj* 2005, pp. 125–131; *Prell* 2012, pp. 171–172; *Watts* 1999). 'Density' indicates the ratio of possible links actually present in a network: theoretically, all nodes in a network could be connected to each other (this would be a density of '1'). A density of '0.1' indicates that 10 % of these possible links exist within a network. The higher the number of nodes, the higher of course the number of possible links. Thus, in general, density tends to decrease with the size of a network. Therefore, it only makes sense to compare the densities of networks of (almost) the same size. Density can be interpreted as one indicator of the relative 'cohesion', but also of the 'complexity' of a network (*Prell* 2012, pp. 166–168; *Kadushin* 2012, p. 29). Other measurements are based on the equal or unequal distribution of quantitative characteristics, such as degree, be-

tweenness or closeness among nodes; a high 'degree centralisation' indicates that many links are concentrated on a relatively small number of nodes, for instance (*Prell* 2012, pp. 168–170). These distributions can also be statistically analysed and visualised for all nodes (by counting the frequency of single degree values) and used for the comparison of networks (see fig. 1 and fig. 2). Certain highly unequal degree distribution patterns (most prominently, power laws) have been interpreted as 'signatures of complexity' of a network (*Newman* 2010, pp. 243–261).

The modelling of networks of routes between places demands further specifications. Links in such models are both weighted (meaning that a quantity is attributed to them) and directed (a link leads from point A to point B, for instance). The aim is to integrate aspects of what *Leif Isaksen* (2008) has called 'transport friction' into calculations; otherwise, the actual costs of communication and exchange between sites, which influenced the frequency and strength of connections, would be ignored in network building. Links could be weighted by using the inverted geographical distance between them, for instance; thus, a link would be the stronger the shorter the distance between two nodes ('distant decay' effect). Of course, if possible, existing information on the (temporal or economic) costs of using specific routes could be used. Otherwise, cost calculation stemming from GIS-based modelling of terrain and routes can be integrated. In riverine transport networks, directed links leading upstream (from point A to point B) would be weighted differently from links leading downstream (from point B to point A) (*Taaffe* and *Gauthier* 1973, pp. 100–158; *Barthélemy* 2011; *Ducruet* and *Zaidi* 2012; *Rodrigue, Comtoi* and *Slack* 2013, pp. 307–317; for historical transport networks cf. *Carter* 1969; *Pitts* 1978; *Gorenflo* and *Bell* 1991; *Graßhoff* and *Mittenhuber* 2009; *Leidwanger, Knappett et al.* 2014; *van Lanen et al.* 2015). Furthermore, there are also measures especially developed for transport networks such as circuitry (or 'alpha index'). It measures the share of the maximum number of cycles or circuits (= a finite, closed path in which the initial node of the linkage sequence coincides with the terminal node) actually present in a traffic network model and thus indicates the existence of additional or alternative paths between nodes in the network and its relative connectivity and complexity (*Taaffe* and *Gauthier* 1973, pp. 104–105; *Rodrigue, Comtoi* and *Slack* 2013, pp. 310–315; *Wang, Ducruet* and *Wang* 2015, p. 455).

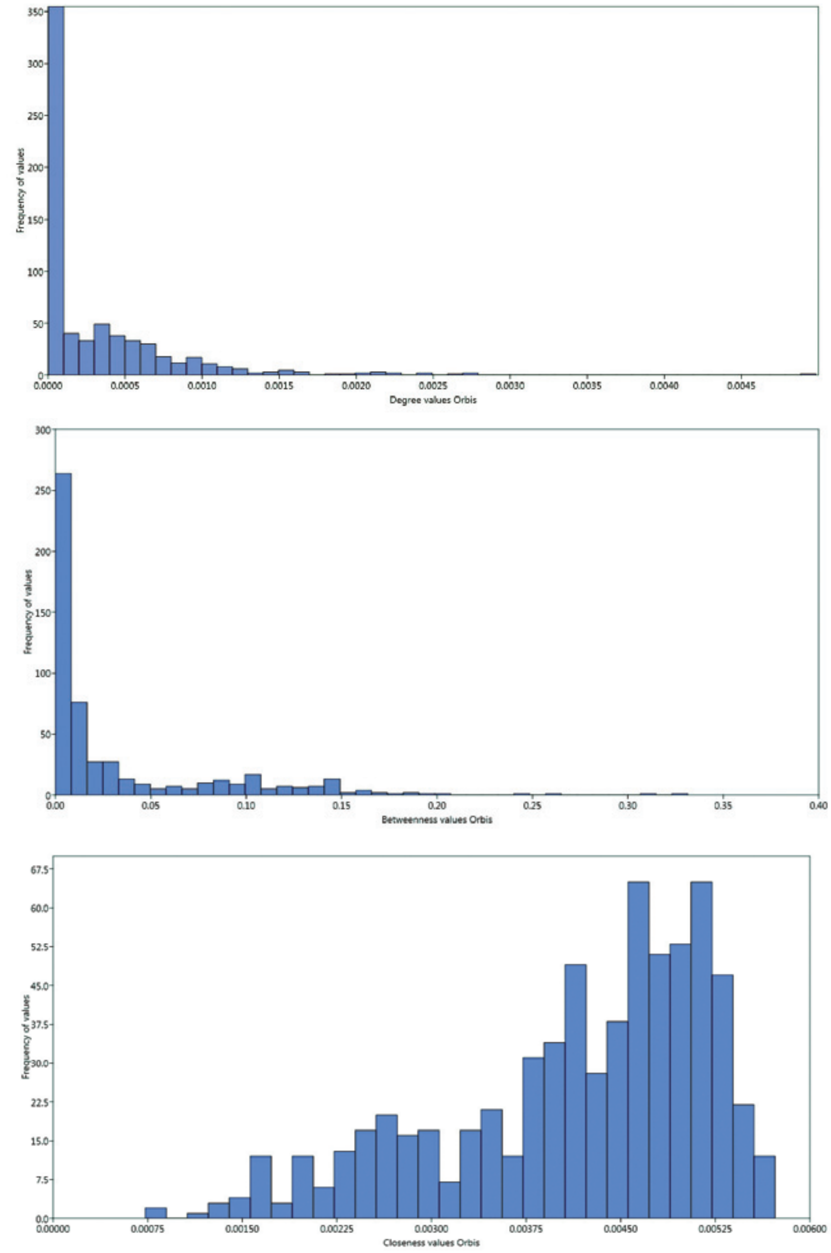

Fig. 1: *Histograms of the distribution of degree values (top), betweenness values (centre) and closeness values (bottom) among all nodes in the ORBIS network model*

Abb. 1: *Histogramme der Verteilung von Degree-Werten (oben), "Betweenness"-Werten (Mitte) und Closeness-Werten (unten) bei allen Knoten im ORBIS-Netzwerk-Modell*

Graph/Diagramm: *J. Preiser-Kapeller*

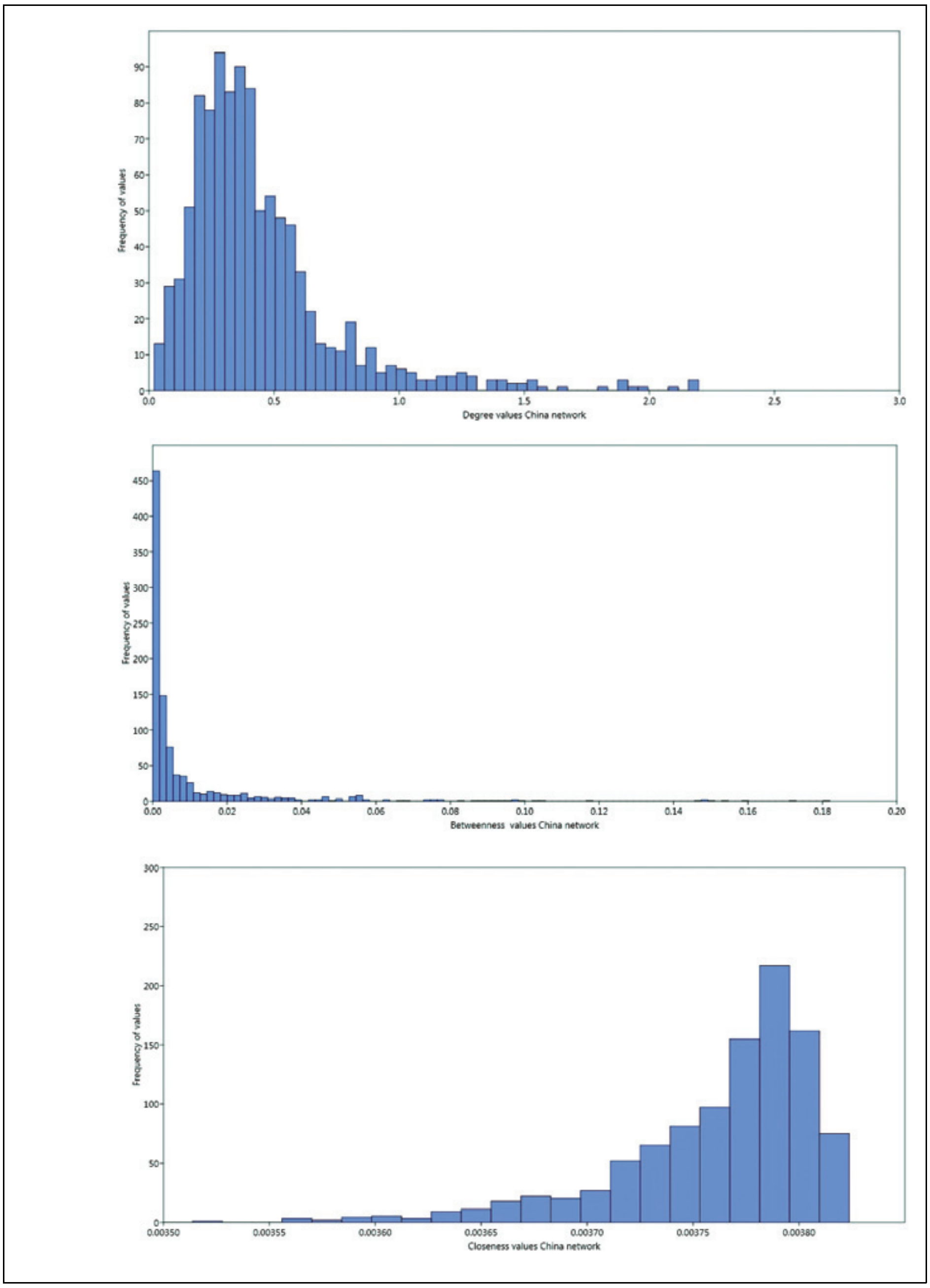

Fig. 2: *Histograms of the distribution of degree values (top), betweenness values (centre) and closeness values (bottom) among all nodes in the China network model*

Abb. 2: *Histogramme der Verteilung von Degree-Werten (oben), »Betweenness«-Werten (Mitte) und Closeness-Werten (unten) bei allen Knoten im China-Netzwerk-Modell*

Graph/Diagramm: *J. Preiser-Kapeller*

Complex network models of empires

As mentioned above, one of the earliest studies in the field of historical network research focused on the analysis of an imperial formation. In 1969, *F.W. Carter* created a network model of the route system in the Serbian Empire of *Stefan Uroš IV Dušan* (r. 1331–1355 CE), using the most important urban centres as nodes and the main trade routes as links. This study also took into account the actual geographical distances between places. Since then, as outlined above, various approaches to model *'transport friction'* have been implemented in studies of historical route systems, ranging from the local to the regional and even *'imperial'* scale.

Table 1: Network measures for the unmodified ORBIS network model and the four modified models with removed links above cost-thresholds

Tab. 1: Netzwerkmaße für das unveränderte ORBIS-Netzwerk-Modell und die vier modifizierten Modelle nach Entfernung der Kanten über Kostenschwellenwerte

ORBIS network model	**Unmod. network**	**W/o links of more than 5 days' travel**	**More than 3 days' travel**	**More than 2 days' travel**	**More than 1 day of travel**
Number of nodes	678	678	678	678	678
Number of edges	1104	1005	870	673	424
Connectedness	1	0.93	0.589	0.325	0.053
Number of isolates	0	13	50	117	246
Density	0.005	0.004	0.004	0.003	0.002
Diffusion (reach of information across the network)	0.986	0.894	0.461	0.256	0.029
Clustering Coefficient (largest component)	0.116	0.12	0.137	0.126	0.131
Fragmentation	0	0.07	0.411	0.675	0.947
Betweenness Centralisation	0.504	0.336	0.216	0.145	0.013
Circuitry (alpha index)	0.32	0.24	0.14	0.00	-0.19
Size of largest component	678	640	519	385	148
Av. range of travel between nodes (largest component, unmod. = 1)	1.00	0.90	0.76	0.61	0.41

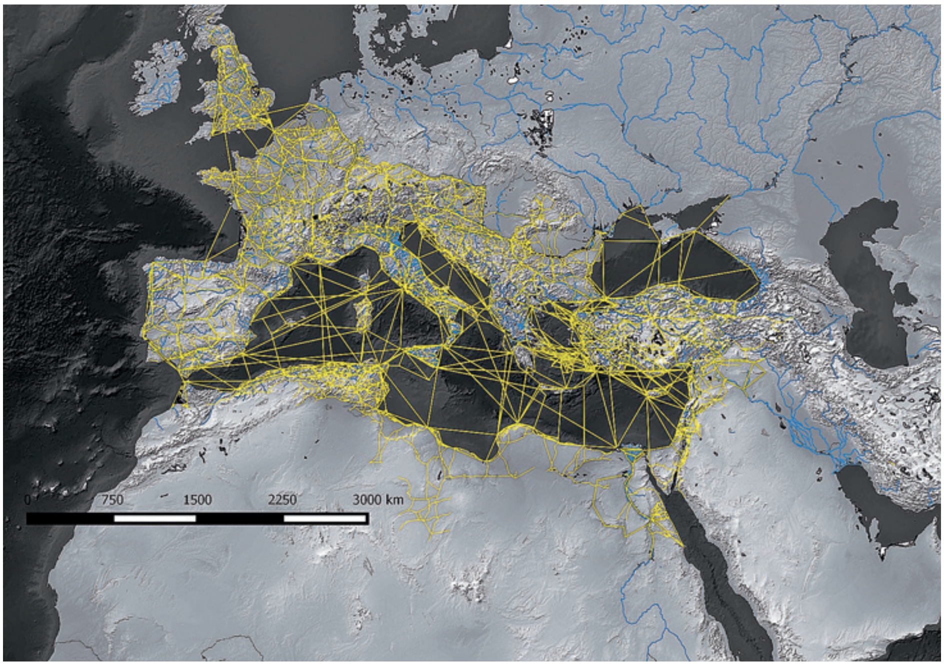

Fig. 3: *Terrestrial, riverine and maritime routes in the ORBIS network model for the Roman Empire*

Abb. 3: *Land-, Fluss- und Seeverbindungen im ORBIS-Netzwerk-Modell für das Römische Reich*

Data/Daten: http://orbis.stanford.edu/; map: *J. Preiser-Kapeller*

The most exhaustive network model of historical sea and land routes of the Imperium Romanum is the *ORBIS Stanford Geospatial Network Model of the Roman World*, developed by *Walter Scheidel* and *Elijah Meeks* (2014) in order to estimate transport cost and spatial integration within the Roman Empire. ORBIS is based on a network of roads, river and sea routes (1104 links in total) between 678 nodes (places), weighted according to the costs of transport (see table 1 and fig. 3).[2] Since it is directed at the entirety of the empire´s traffic system, ORBIS is less detailed on the regional and local level than network models for smaller areas (see for instance *Orengo* and *Livard*a 2016). We have corrected these data (especially with regard to the locations of some places) and modified the network model, so that the link between two nodes (places) is the stronger the smaller the

2 The dataset was downloaded from: https://purl.stanford.edu/mn425tz9757 (Creative Commons Attribution 3.0 Unported License). For a similar model, see also *Graham* 2006. We are currently preparing the data for the Chinese network model to be made available for free via https://github.com.

costs of overcoming the distance between them is, thus reflecting the ease or difficulty of transport and mobility between two localities (see also *Preiser-Kapeller* 2019).

For Imperial China, unfortunately there is no similar geospatial network model. In 2015 *Chengjin Wang*, *César Ducruet* and *Wang Wei* tried to reconstruct the road networks in China from 1600 BCE to 1900 CE on the basis of historical data and maps, but (to our knowledge) did not make their data available as *Scheidel* and *Meek* did. The same is true for an earlier study of *Wang* and *Ducruet* (2013) on the Chinese port system between 221 BCE and 2010 CE. A rich set of historical-geographical data across periods, however, is provided online via the China Historical Geographic Information System (CHGIS) hosted at Harvard University.[3] Based on these data, we constructed a network model of the most important riverine and land routes covering the historical central provinces of imperial China (cf. also *Brook* 1998). The model includes 1034 nodes (places) and 3034 links, weighted according to the cost of transport (based on geographical distance) (see table 2 and fig. 4). Similar to the ORBIS model, it aims to cover the entirety of the pre-modern traffic system in the Chinese Empire and is thus less detailed on the regional and local level. Equally, in the absence of suitable data, maritime links are missing; but since they played a relatively peripheral role (when compared with the Roman Mediterranean, for instance), we assume that essential aspects of the transport network can still be captured with our model (*Brook* 1998, pp. 615–619; *Wang* and *Ducruet* 2013; *Schottenhammer* 2015; see also the pioneering studies of *Skinner* 1977).

Table 2: Network measures for the unmodified China network model and the four modified models with removed links above cost-thresholds

Tab. 2: Netzwerkmaße für das unveränderte China-Netzwerk-Modell und die vier modifizierten Modelle nach Entfernung der Kanten über Kostenschwellenwerte

China network model	**Unmod. network**	**W/o links of more than 5 days' travel**	**More than 3 days' travel**	**More than 2 days' travel**	**More than 1 day of travel**
Number of nodes	1034	1034	1034	1034	1034
Number of edges	3034	2788	2056	1029	315
Connectedness	1	0.985	0.935	0.254	0.003
Number of isolates	0	2	5	37	353
Density	0.011	0.01	0.008	0.004	0.001
Diffusion (reach of information across the network)	1	0.975	0.922	0.248	0.003

3 http://sites.fas.harvard.edu/~chgis/.

China network model	Unmod. network	W/o links of more than 5 days' travel	More than 3 days' travel	More than 2 days' travel	More than 1 day of travel
Clustering Coefficient (largest component)	0.65	0.643	0.62	0.478	0.133
Fragmentation	0	0.015	0.065	0.746	0.997
Betweenness centralisation	0.173	0.395	0.302	0.123	0
Circuitry (alpha index)	0.97	0.85	0.50	0.00	–0.35
Size of largest component (number of nodes)	1034	1026	1000	478	20
Av. range of travel between nodes (largest component, unmod. = 1)	1	0.9	0.75	0.5	0.272

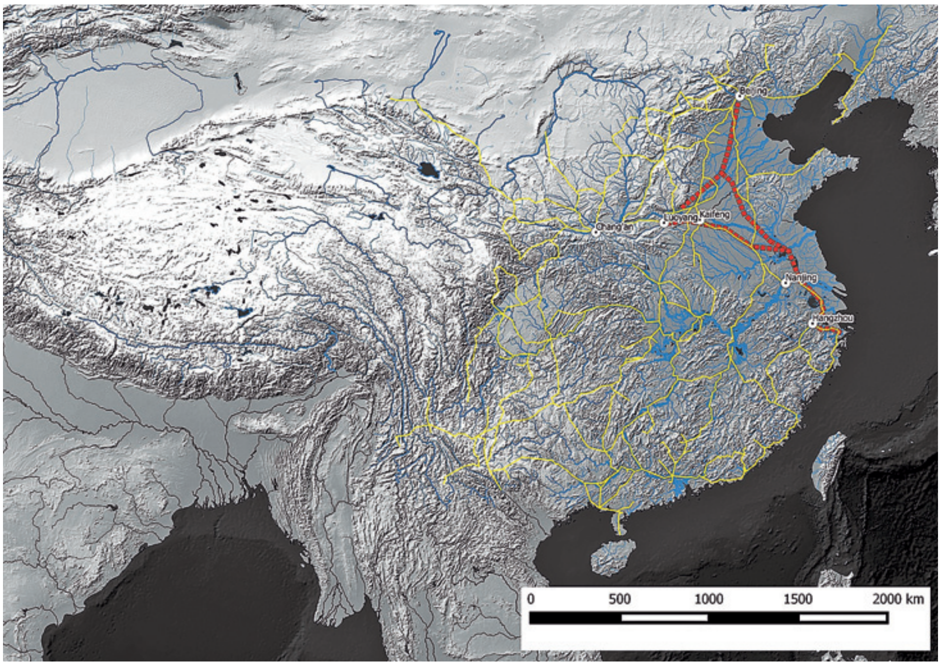

Fig. 4: *Terrestrial, riverine and canal routes in the network model for Imperial China (Red = Grand Canal system)*

Abb. 4: *Land-, Fluss- und Kanalverbindungen im China-Netzwerk-Modell für das Chinesische Reich (Rot = Kaiserliches Kanalsystem)*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; map: *J. Preiser-Kapeller*

Networks are of course dynamic: relationships may be established, maintained, modified or terminated; nodes appear in a network and disappear (also from the sources). The common solution to capture at least part of these dynamics is to define 'time-slices' (divided through meaningful caesurae in the development of the object of research, as defined by the researcher's knowledge of the material) and to model distinct networks for each of them. Yet, since we reckon with a relatively long-term stability of core elements of the route and infrastructure networks we are trying to model (and for the sake of simplicity), we decided to use static models (*de Nooy, Mrvar* and *Batagelj* 2005, pp. 92–95; *Lemercier* 2012, pp. 28–29; *Batagelj et al.* 2014). Equally, routes and infrastructures are only one 'layer' of the various networks spanning across an imperial space, such as administration, commerce or religion. All these categories of connections could be integrated into a 'multi-layer' network model but, unfortunately, we do not possess the same density of evidence for them across the entire empires as we have for the routes. At the same time, these flows of people and ideas were much more volatile than the infrastructural web, on which all these other categories of linkages depended. As we will show below in the case of epidemics, the structure of the underlying route networks also influenced the pattern of diffusion of these other imperial network 'layers' (*Collar* 2013; *Auyang* 2015; on multi-layer networks see *Bianconi* 2018). Against this background, we stress the famous aphorism that *"all models are wrong but some are useful"*.[4]

In a first step, we analysed the spatial and statistical distribution of measures of centrality among the nodes (= places) of the network. The number and accumulated strength of links of a node (its weighted degree, cf. *Newman* 2010, pp. 168–169) are high, with many localities connected among each other over short distances via the most convenient transport medium – in the Roman case the sea (such as in the Aegean), in China riverine routes (such as in the densely settled delta area of the Yángz Jiāng) (see fig. 5 and fig. 6). Statistically, the distribution of these degree values is very unequal, with a high number of nodes with a relatively low degree of centrality and a small number of 'hubs' with high centrality values (see fig. 1 and fig. 2). As indicated above, betweenness measures the relative centrality of a node in the entire network due to its position on many (or few) potential shortest paths between nodes (*Newman* 2010, pp. 185–193). In the ORBIS network, maritime transport hubs (such as Alexandria, Rhodes or Messina) serve as the most important integrators of the entire system in this regard. Other hotspots of connectivity are located on the main routes between the Northern provinces and the Mediterranean core (between Gaul and Spain, Central Europe and Italy, or the Lower Danube and the Aegean, respectively Constantinople)

4 The full version of this saying attributed to the statistician George Box sounds even more flattering for our purpose: *"Since all models are wrong the scientist cannot obtain a 'correct' one by excessive elaboration. On the contrary, following William of Occam he should seek an economical description of natural phenomena. Just as the ability to devise simple but evocative models is the signature of the great scientist so over-elaboration and over parameterization is often the mark of mediocrity."* Cf. https://en.wikipedia.org/wiki/All_models_are_wrong.

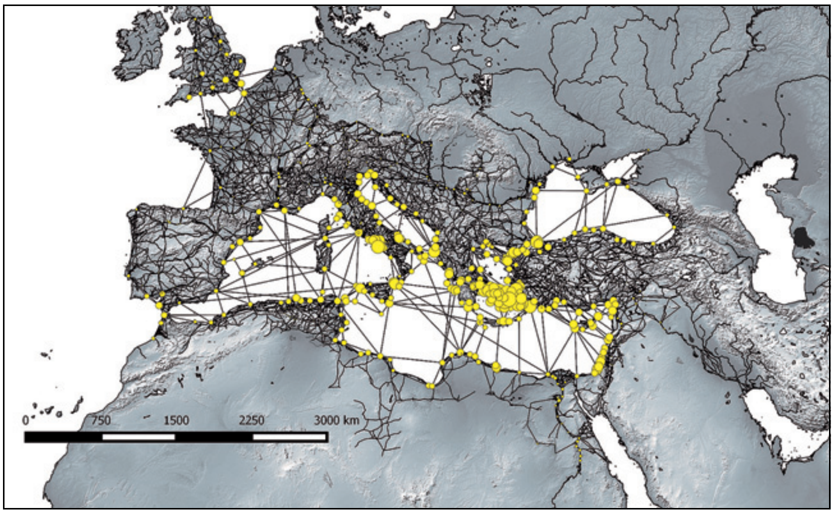

Fig. 5: *Spatial distribution of degree values of nodes in the ORBIS network model for the Roman Empire*

Abb. 5: *Räumliche Verteilung von Degree-Werten der Knoten im ORBIS-Netzwerk-Modell für das Römische Reich*

Data/Daten: http://orbis.stanford.edu/; calculations and map: *J. Preiser-Kapeller*

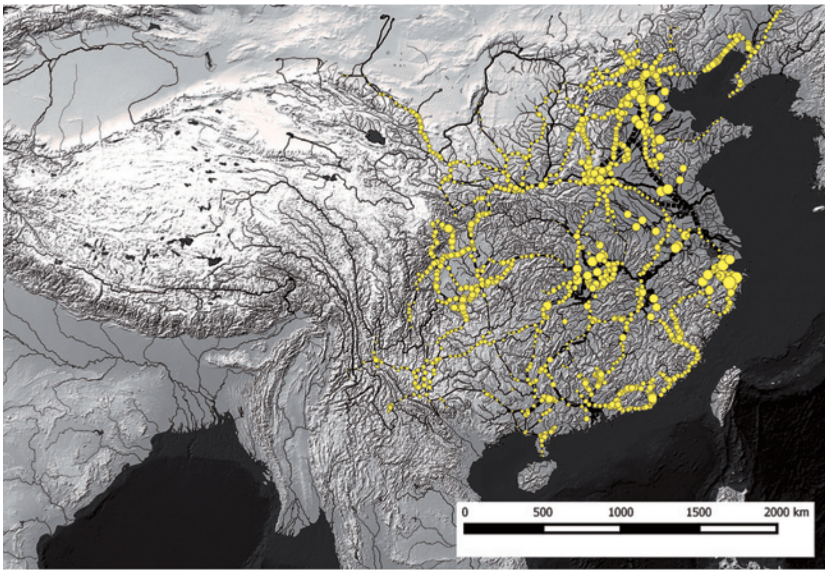

Fig. 6: *Spatial distribution of degree values of nodes in the network model for Imperial China*

Abb. 6: *Räumliche Verteilung von Degree-Werten der Knoten im China-Netzwerk-Modell für das Chinesische Reich*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

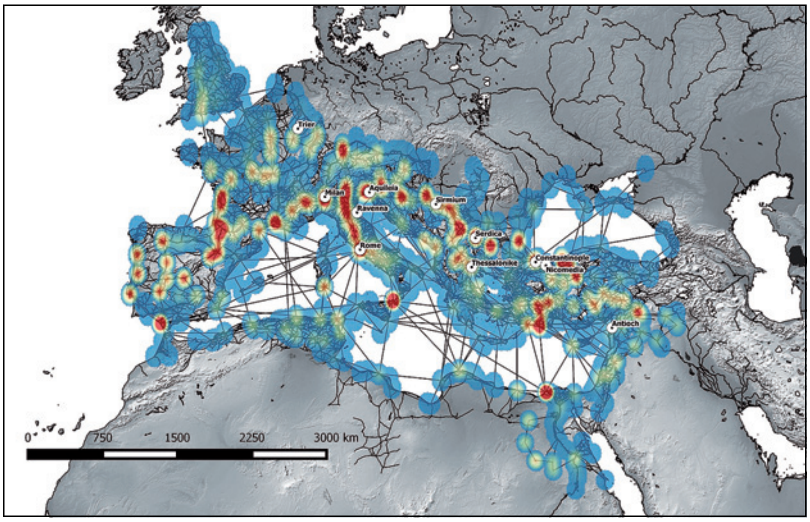

Fig. 7: Heat map of the spatial distribution of betweenness values of nodes in the ORBIS network model for the Roman Empire

Abb. 7: Heatmap der räumlichen Verteilung von »Betweenness«-Werten der Knoten im ORBIS-Netzwerk-Modell für das Römische Reich

Data/Daten: http://orbis.stanford.edu/; calculations and map: *J. Preiser-Kapeller*

(see fig. 7). In the China network, the intermediary zones between West and East along the main riverine arteries of the Huang He and the Yángz Jiāng can be identified as betweenness hotspots (see fig. 8). At the same time, the statistical distribution of betweenness values is even more unequal than that of degree centrality (see fig. 1 and fig. 2). 'Closeness' measures the average length of all paths between a node and all other nodes in a network and indicates its overall 'reachability' (or remoteness) (*Wassermann* and *Faust* 1994, pp. 184–188). Statistically, closeness values are relatively equally distributed (see fig. 1 and fig. 2). Their spatial distribution in the ORBIS model indicates again the significant role played by maritime connectivity as well as the intermediary regions between the Northern provinces and the Mediterranean core for the cohesion of the network (see fig. 9). In the China network, again the regions along the main riverine routes as well as the Grand Canal (constructed to connect the two river systems of the Huang He and the Yángz Jiāng especially for feeding the imperial capitals since the 7^{th} century CE, see below) are privileged regarding closeness centrality (see fig. 10). Both networks are equally characterised (relative to their size) by high values of circuitry (see tables 1 and 2) (for similar findings cf. *Wang, Ducruet* and *Wang* 2015).

The spatial distributions of network centrality measures in the two models confirm well-established assumptions on the inherent transport logics of these imperial systems. Their statistical distribution patterns (see fig. 1 and fig. 2) can equally be interpreted as 'signatures of complexity', thus identifying both imperial systems (or their imperfect reproduction in the two models) as 'large-scale complex

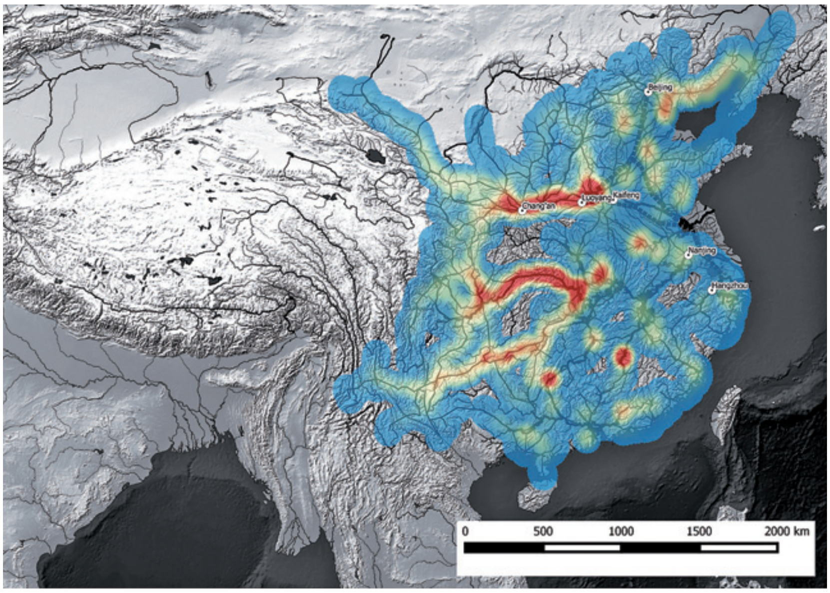

Fig. 8: *Heat map of the spatial distribution of betweenness values of nodes in the network model for Imperial China*

Abb. 8: *Heatmap der räumlichen Verteilung von »Betweenness«-Werten der Knoten im China-Netzwerk-Modell für das Chinesische Reich*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

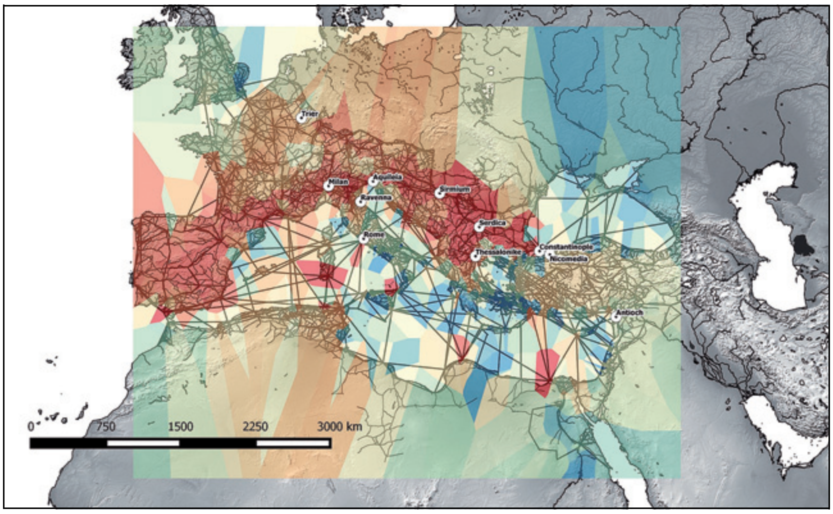

Fig. 9: *Coloured Voronoi-map of the spatial distribution of closeness values of nodes in the ORBIS network model for the Roman Empire*

Abb. 9: *Farbiges Voronoi-Diagramm der räumlichen Verteilung von Closeness-Werten der Knoten im ORBIS-Netzwerk-Modell für das Römische Reich*

Data/Daten: http://orbis.stanford.edu/; calculations and map: *J. Preiser-Kapeller*

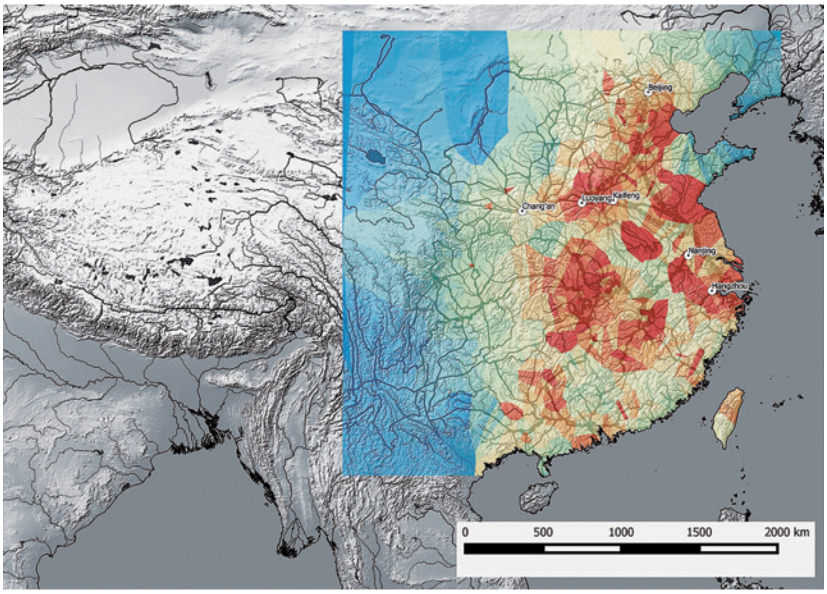

Fig. 10: *Coloured Voronoi-map of the spatial distribution of closeness values of nodes in the network model for Imperial China*

Abb. 10: *Farbiges Voronoi-Diagramm der räumlichen Verteilung von Closeness-Werten der Knoten im China-Netzwerk-Modell für das Chinesische Reich*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

networks' (for similar distribution patterns emerging from an analysis of Roman urbanisation in Asia Minor, cf. *Hanson* 2011). They show 'non-trivial' topological properties and patterns of connectivity between their nodes *"that are neither purely regular nor purely random"*; besides the high inequality in the distributions of centrality measures, these include a high value of circuitry and (as we will demonstrate below) a hierarchical community structure. These properties also allow for some assumptions on the overall robustness and tolerance towards the failure of nodes or links of these networks (*Newman* 2010, pp. 591–625; *Estrada* 2012, pp. 187–214; *Preiser-Kapeller* 2015; *Barabási* 2016, pp. 113–145, 271–305 and 321–362).

Empire-wide connectivity, imperial capitals and ecologies

A main aim of the pioneering study of *F.W. Carter* (1969, pp. 54–55) mentioned earlier was to *"learn more about the position"* of the *"successive capitals"* within the route network of the Serbian Empire and *"whether Stefan Du¹an made the right choice in Skopje as his capital"*. Tsar *Dušan* did not, according to the findings of *Carter,* and thus (in *Carter´*s opinion) diminished the prospect for the sustainability of his empire, since his residence of choice did not rank among the most central nodes in the network model. Other places would have been better situated, *Carter* argued, and thus would have provided better opportunities for economic development, the ease of 'troop movement' as well as the flows of materials.

Especially the aspect of material flows can be connected with the more recent concept of 'imperial ecology', which *Sam White* (2011) in his study on the Ottoman Empire in the 16th and 17th century CE has defined as the *"particular flows of resources and population directed by the imperial center"* on which its success and survival depended. Within the web of the imperial ecology, in turn, the supply of the imperial centre (what has been called its 'urban metabolism') can be identified as a core element (*González de Molina* and *Toledo* 2014; *Forman* 2014; *Schott* 2014). With regard to its dependence on the scale and reach of its network, *Peter Baccini* and *Paul H. Brunner* (2012, p. 58) made clear that the city of Rome in the imperial period had become *"an example of a system that could only maintain its size […] on the basis of a political system that guaranteed the supply flows"* (see also *Fletcher* 1995; *Morley* 1996). The administrators and later the emperors of Rome invested heavily in the infrastructure of the city. Roman roads were built especially for military purposes (beginning with the Via Appia in 312 BCE leading from Rome to Capua and in 190 BCE expanded towards Brundisium on the Adriatic Sea); their maximum extent was 80,000 to 100,000 km (*Kolb* 2000; *Sauer* 2006; *Schneider* 2007, pp. 72–75, 89; *Klee* 2010; *Ruffing* 2012, pp. 42–43). Maritime links on the other hand served for the transport of bulk goods and became increasingly important for the provision of the growing capital. From 123 BCE onwards, Rome became dependent on consignments of grain from North Africa, which at that time were financed by the taxes from the recently acquired territories in Western Asia Minor, thus establishing an early core triangle of flows within the imperial ecology (*Erdkamp* 2005; *Ruffing* 2012, pp. 98–99; *Sommer* 2013, pp. 90–91). Rome´s earlier harbour, Ostia, was augmented with the immense artificial installations at Portus under Emperor *Claudius* (41–54 CE), later expanded by Emperor *Trajan* (98–117 CE) (*Davies* 2005; *Scheidel, Morris* and *Saller* 2007, pp. 570–618; *Keay* 2012). Thus, it was essential for both the coordination of imperial rule and the very existence of the city that Rome remained well positioned in the growing network of routes. The orientation of these networks onto the capital was also symbolised with the *Milliarium Aureum*, the golden milestone erected by Emperor Augustus in 20 BCE on the Forum Romanum as the point of origin of all roads in the empire (*Kolb* 2000; *Klee* 2010; *Temin* 2013). In addition, an analysis of the centrality measures for Rome within the ORBIS network demonstrates its high connectivity, both with regard to betweenness and closeness values (see table 3; cf. also *Morley* 1996, pp. 63–68). For the network at large, ranging from Britannia to Egypt and from Spain to the Euphrates, Rome is however not necessarily any longer the most central hub (see table 3). Especially after the severe military and political crisis of the 3rd century CE, strategic considerations also demanded the relocation of imperial residences on a more permanent basis to places near the endangered frontier zones (*Johne* 2008; *Pfeilschifter* 2014). These cities, such as Milan, Aquileia, Sirmium or Serdica, also show up in the analysis of the network model as well-connected with regard to their betweenness and closeness values (see table 3), being situated, as mentioned earlier, in the intermediary areas between the northern frontier and the Mediterranean core (see fig. 7 and fig. 9). In terms of urban scale and population size, these places could of course not compete with Rome, which remained privileged with respect to the inflows of supplies from across the Mediterranean (*Erdkamp* 2005; *Scheidel, Morris* and *Saller* 2007, pp. 651–671). It was only the 'new Rome' of Constantinople, inaugurated by Emperor Constantine I in 330 CE, that would eventually outperform the old capital on the Tiber in these aspects in the 5th century CE. Constantinople is also the only one among the eleven imperial capitals in our sample that ranks in the ORBIS network model among the top ten in all three centrality measures of degree, betweenness and closeness (see table 3). This may contribute to an explanation of its long-time 'success' as an imperial centre over almost 1600 years until 1923 CE (the fall of the Ottoman dynasty), much longer than Rome itself (*Teall* 1959; *Mango* and *Dagron* 1995; *Preiser-Kapeller* 2018, pp. 249–250).

Table 3: Scaled node centrality measures for selected Roman imperial residential cities in the ORBIS network model (the position of a city within centrality rankings for all nodes of the network is only indicated if among the top 20)

Tab. 3: Skalierte Knotenzentralitätsmaße für ausgewählte Wohnstädte des Römischen Kaiserreiches im ORBIS-Netzwerk-Modell (die Lage einer Stadt innerhalb der Zentralitätskennziffern für alle Knoten des Netzwerks ist nur angegeben, wenn sie zu den oberen 20 gehört)

Cities (in alphabetic order)	**Degree [scaled, network mean = 1] (rank)**	**Betweenness [scaled, network mean = 1] (rank)**	**Closeness [scaled, network mean = 1] (rank)**
Antioch	0.35	0.29	0.99
Aquileia	2.92	5.38	1.29
Constantinople	6.70 (9)	6.61 (10)	1.34 (10)
Milan	0.24	4.82	1.31
Nicomedia	2.04	0.34	1.08
Ravenna	2.32	0.03	1.11
Rome	0.85	4.33	1.11
Serdica	0.02	9.23 (4)	1.35 (4)
Sirmium	0.11	4.11	1.30
Thessalonike	0.92	3.22	1.24
Trier	0.15	0.21	1.14

Similar observations can be made for China; the cities of Chang´an and Luoyang (see fig. 4) had served as capitals in the period of the Han dynasty (206 BCE to 220 CE) and as starting points for the emerging imperial road system (which under the Han extended over 35,000 km). Both were located on rivers, which would allow for an easier inflow of resource into these urban centres that competed in scale with imperial Rome (*Lewis* 2007; *Tuan* 2008, pp. 75–81; *Wang, Ducruet* and *Wang* 2015, pp. 457–465; *Auyang* 2015, pp. 152–154; *Marks* 2017, pp. 90–93). Moreover, both Chang´an and Luoyang were selected as residences again after the 'reunification' of China by the Sui in the late 6th and early 7th century CE. Emperor *Yang* (604–617 CE), in an edict of 17 December 604 CE, made clear that his decision to establish his residence in Luoyang was based on both tradition and its position in the network of imperial ecology: *"Luoyang has been a capital since antiquity. Within the precincts of its royal territory, Heaven and Earth merge with each other; yin and yang work in harmony. Commanding the Sanhe region, it is safeguarded by four mountain passes. With excellent land and water transportation, it provides a whole gamut of taxes and tribute"* (*Xiong* 2006, pp. 76–78). *Yang* and his father, Emperor *Wendi* (581–604 CE), also began the construction of the Grand Canal system (see fig. 4), which connected the new breadbaskets in the south along the Yángz Jiāng with the traditional imperial centres in the north and became a main lifeline of the imperial ecology for the next millennium. The stress on society created by all these large-scale building projects, together with a series of costly and unsuccessful military campaigns, eventually contributed to the fall of Emperor *Yang*. Yet, the succeeding Tang Emperors equally built on the same system of capitals and metabolic flows (*Elvin* 1973, pp. 131–145; *Xiong* 2006; *Tuan* 2008, pp. 94–100; *Lewis* 2009, pp. 86–101 and 113–118; *Wang* and *Ducruet* 2013; *Marks* 2017, pp. 135–137; *Xiong* 2017). In terms of network analysis, both Chang´an and Luoyang are situated in a corridor of high betweenness on the main West-East axis in the northern Chinese heartlands along the Huang He (see fig. 8 and fig. 10). Luoyang, however, ranks higher than Chang´an with regard to closeness centrality and far higher in its degree value, which reflects its more direct integration into the Grand Canal system (see table 4). Luoyang is equally identified as a 'core node' from the Qin dynasty to the Sui-Tang period in the calculations of *Wang, Ducruet* and *Wang* (2015). The supply of Chang´an, by contrast, became more and more of a burden for the 'imperial ecology'; its immediate hinterland was frequently beset by drought and erosion, diminishing crop yields. Already in the early 7th century CE, the court official Gao Jifu (d. 651) had criticised the Tang´s decision to establish a residence there, since *"land is limited, and the people live densely together. Agriculture is not yielding. Beans and millet are cheap, but the stocks are not large"* (*Thilo* 2006, p. 183). So many more of the estimated one to two million habitants of Chang´an and of the many military garrisons nearby depended on the inflow of supplies via the canal network. Yet, in contrast to Luoyang, Chang´an was not connected to the Grand Canal directly, but via the River Wei (which frequently changed its course and water level) respectively by minor canals running parallel. The amount of grain which could be transported to the capital thus fluctuated between four million and 100,000 bushels. If supplies collapsed, the Tang emperors and the royal household had to relocate over 320 km to the east, to Luoyang. This immensely expensive operation took place 14 times in the century between 640 and 740 CE, half of these occasions having been caused by supply shortfalls (*Thilo* 1997; *Elvin* 2004; *Thilo* 2006, pp. 193–194; *Lewis* 2009, p. 37; *von Glahn* 2016; *Xiong* 2017; *Preiser-Kapeller* 2018, pp. 237–238). Even when a new canal eased the situation from 743 CE onwards, the demands of the centre remained burdensome for the imperial ecology.

Table 4: Scaled node centrality measures for selected Chinese imperial residential cities in the China network model (the position of a city within centrality rankings for all nodes of the network is only indicated if among the top 20)

Tab. 4: Skalierte Knotenzentralitätsmaße für ausgewählte Hauptstädte des Chinesischen Kaiserreiches im China-Netzwerk-Modell (der Rang einer Stadt innerhalb der Zentralitätskennziffern für alle Knoten des Netzwerks ist nur angegeben, wenn sie zu den oberen 20 gehört)

Cities (in alphabetic order)	**Degree [scaled, network mean = 1] (rank)**	**Betweenness [scaled, network mean = 1] (rank)**	**Closeness [scaled, network mean = 1] (rank)**
Beijing	2.28	11.91 (11)	1.0166
Chang´an	0.74	11.16 (13)	1.0109
Hangzhou	4.77 (4)	3.85	1.0187
Kaifeng	3.60 (12)	18.38 (3)	1.0208 (4)
Luoyang	3.50 (13)	11.52 (12)	1.0206 (8)
Nanjing	2.86	4.38	1.0195 (18)

In 742 CE, for instance, 36 % of all grain collected by the imperial administration and 48 % of all textiles paid as taxes had to be transported to Chang´an and its surrounding area. Like imperial Rome, the urban metabolism of the Tang capital almost entirely depended on the working of the tax and distribution networks of the entire empire – and its less well-situated position, as also reflected in the network model, intensified the stress on the imperial ecology (*Thilo* 1997; *Thilo* 2006, 199–200; *Xiong* 2006; *von Glahn* 2016). Consequently, when the control of the Tang over the empire dwindled in the 9th century CE and made room for political fragmentation towards the end of that century, Chang´an shrank in scale and was officially abandoned in 904 CE. Characteristically, the court relocated to Luoyang, but there too the *Tang* rule ended in 907 CE. Only the Song succeeded in reuniting most areas of China from 960 CE onwards; their new capital became Kaifeng (see fig. 4), which was even better located within the supply systems than Luoyang and surrounded by *“an intensive trade and communication zone”*, as *William Guanglin Liu* (2015, p. 91) has stated. This is also reflected in our network analysis, where Kaifeng ranks fourth of all nodes in closeness and third in

betweenness centrality (see table 4). However, when the Song lost the north of China to the Jin in 1126/1127 CE, they had to relocate their capital to Hangzhou further south. This site is equally well-connected in network analytical terms (ranking fourth of all nodes in degree in our model, see table 4) and near the open sea (see fig. 8 and fig. 10), thus reflecting the increasing importance of maritime trade (which, as mentioned above, is unfortunately not reflected in our model) (*Twitchett* 1979, pp. 696, 720–728; *Thilo* 2006, pp. 24–28; *Tuan* 2008, pp. 132–135; *Kuhn* 2009, pp. 72–73, 224–227; *Mostern* 2011; *Brooke* 2014, pp. 347–348; *Liu* 2015, pp. 77–95; *Schottenhammer* 2015). The Mongols after their conquest of China (between 1235 and 1279 CE) established their capital at Khanbaliq/Dadu (present-day Beijing), which was much more to the north than earlier capitals, but near the former capital Zhongdu of the Jin dynasty and to the regions of origin of the new Mongol Yuan dynasty (see fig. 8 and fig. 10). When the Ming expelled the Yuan in 1368, the Ming kept Beijing as their 'northern capital' in addition to Nanjing as their 'southern capital' in the region where their rule had started. Both places became integrated into the Grand Canal network, which was extended towards the north. Both sites are also well-connected in network terms (see fig. 8 and fig. 10), but Beijing ranks much higher in betweenness centrality (see table 4), also reflecting its strategic position on the routes towards the northern frontier, which became a permanent military challenge for the Ming (*Elvin* 1973; *Barfield* 1989; *Brook* 1998; *Brook* 2010; *Liu* 2015, pp. 106–120). In 1644, the Manchu, coming from the North-East, captured the city and established the Ch'ing as the last dynasty of imperial China (until 1911); they made Beijing China´s sole capital (*Huang* 1988, pp. 180–191; *Mote* 1999, pp. 813–911; *Peterson* 2002, pp. 563–640; *Elvin* 2004).

Following *Carter*, the application of network models confirms the idea that the position of capitals within the web of routes and corridors contributes to their emergence as centres and is, in turn, reinforced by the alignment of infrastructures on their demands. Increased connectivity within the imperial ecology, however, also had unintended consequences, such as facilitating the spread of epidemics. Under the early Tang, a major contagion between 636 and 643 spread from Chang´an to the east primarily along the recently established axes of the Grand Canal System, reaching Luoyang and Kaifeng (see fig. 11). Equally, epidemics under the Ming in 1588 and 1642 CE (see fig. 12 and fig. 13) followed the main corridors of connectivity (by closeness centrality) identified in our network analysis (*Elvin* 2004; *Marks* 2017, pp. 146–148). For the three major epidemics registered in Roman imperial times (the Antonine plague in 165–180 CE, the Plague of Cyprian in 249–262 CE and the Plague of Justinian, whose waves afflicted the Mediterranean between 540 and 750 CE), the data on their spatial diffusion are unfortunately much sparser. However, for the first outbreak of Justinian´s Plague in the 540s, probable corridors of spread show equally a high overlap with the zones of high closeness-centrality marked in our analysis of the ORBIS network (see fig. 14). Imperial ecologies thus also became disease ecologies, the later using the networks of the former (*McCormick* 2003; *Stathakopoulos* 2004; *Little* 2006; *Cliff* and *Smallman-Raynor* 2009; *Harper* 2017; *Bianconi* 2018, pp. 58–66).

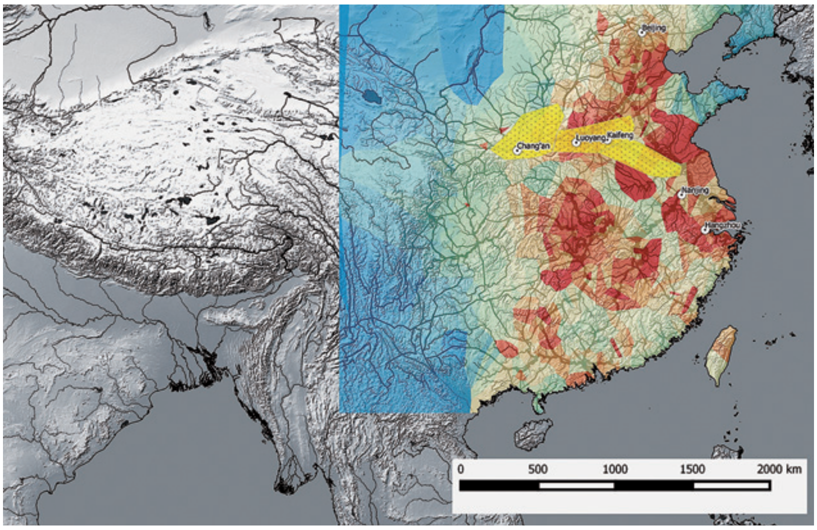

Fig. 11: *The spread of a major epidemic in 636 to 643 CE (yellow) on a coloured Voronoi-map of the spatial distribution of closeness values of nodes in the network model for Imperial China*

Abb. 11: *Ausbreitung einer schweren Epidemie in den Jahren 636–643 n. Chr. (gelb) auf einem farbigen Voronoi-Diagramm der räumlichen Verteilung von Closeness-Werten der Knoten im China-Netzwerk-Modell für das Chinesische Reich*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

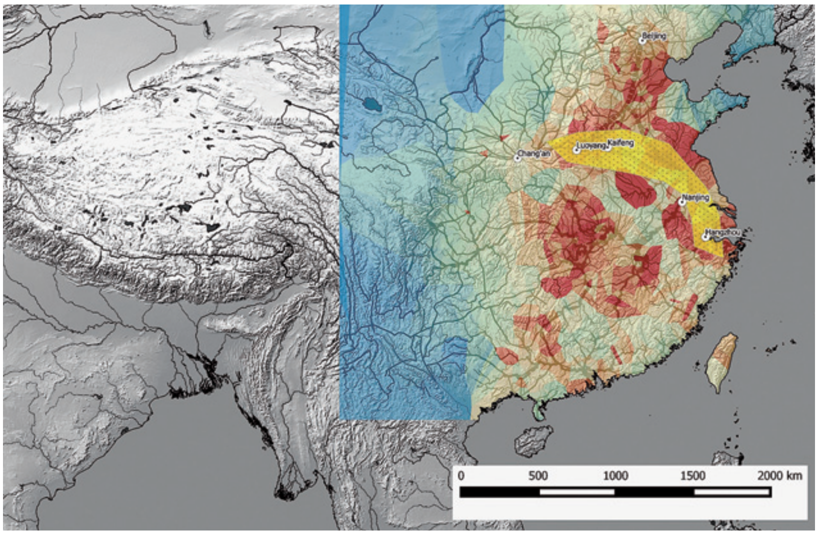

Fig. 12: *The spread of a major epidemic in 1588 CE (yellow) on a coloured Voronoi-map of the spatial distribution of closeness values of nodes in the network model for Imperial China*

Abb. 12: *Ausbreitung einer schweren Epidemie im Jahre 1588 n. Chr. (gelb) auf einem farbigen Voronoi-Diagramm der räumlichen Verteilung von Closeness-Werten der Knoten im China-Netzwerk-Modell für das Chinesische Reich*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

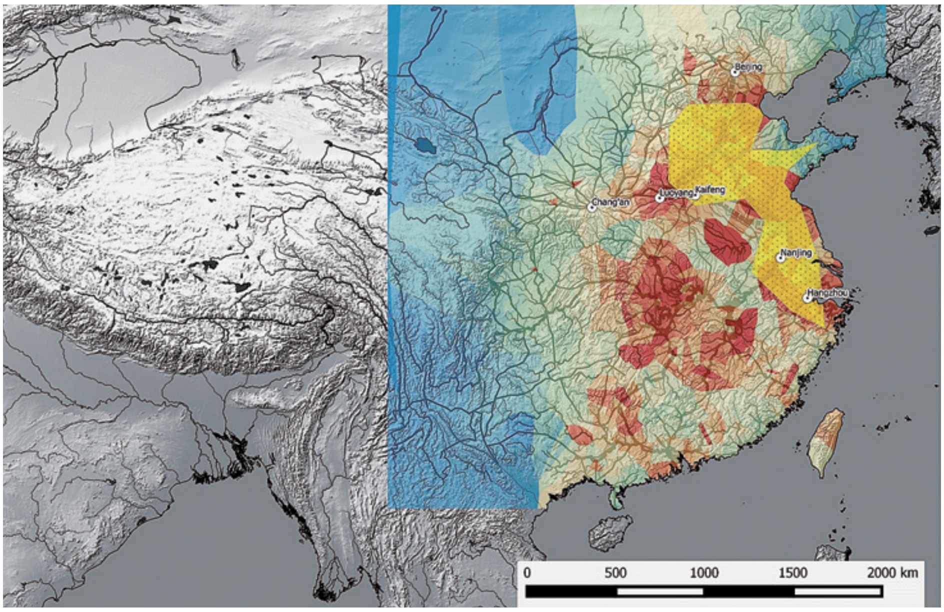

Fig. 13: The spread of a major epidemic in 1642 CE (yellow) on a coloured Voronoi-map of the spatial distribution of closeness values of nodes in the network model for Imperial China

Abb. 13: Ausbreitung einer schweren Epidemie im Jahre 1642 n. Chr. (gelb) auf einem farbigen Voronoi-Diagramm der räumlichen Verteilung von Closeness-Werten der Knoten im China-Netzwerk-Modell für das Chinesische Reich

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

The city of Rome had, however, already experienced a significant reduction in size by the mid-6th century, which had not been caused by the plague; as Baccini and Brunner underline, *"the drastic shrinking was not due to an ecological collapse but to an institutional breakdown. The metabolism of such large systems is not robust because it cannot maintain itself without a huge colonized hinterland. It has to reduce its population to a size that is in balance with its economically and ecologically defined hinterland"* (*Baccini* and *Brunner* 2012, p. 58). The urban shrinking of Rome was one consequence of the breakdown of central rule and the fragmentation of the imperial networks (and ecology) in the western provinces in the 5th century CE. This process is traditionally marked with the sacks of Rome in 410 and 455 CE, the loss of the vital breadbasket of North Africa to the Vandals (between 429 and 439 CE) and finally the dismissal of Emperor Romulus Augustulus in 476 CE (who characteristically had his residence in Ravenna) (*Börm* 2013; *Preiser-Kapeller* 2016; *Preiser-Kapeller* 2018, pp. 224–225). This leads to the question of the robustness and the possible dynamics of fragmentation of imperial networks.

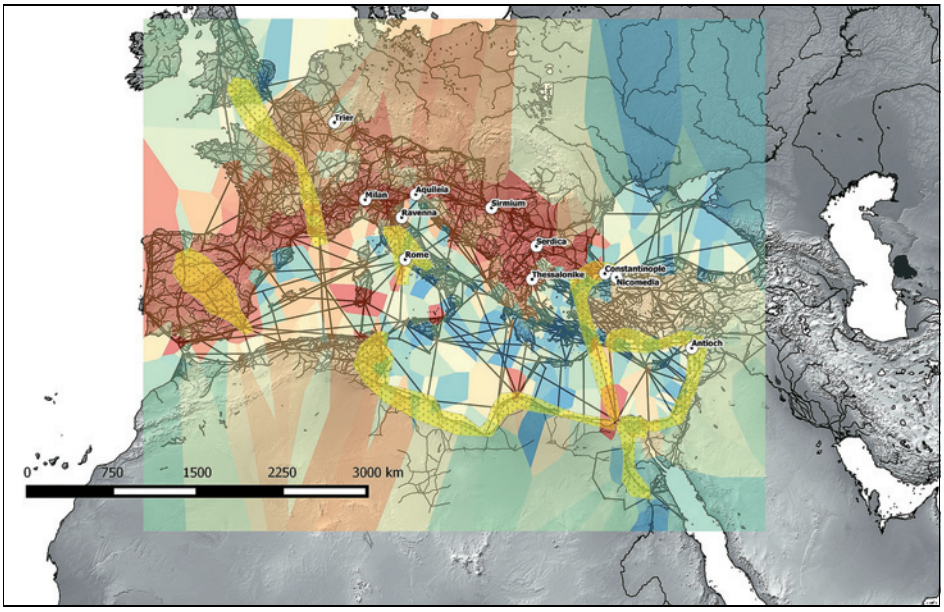

Fig. 14: *Possible corridors of diffusion of Justinian´s Plague in the 540s CE (yellow) on a coloured Voronoi-map of the spatial distribution of closeness values of nodes in the ORBIS network model for the Roman Empire*

Abb. 14: *Mögliche Korridore der Verbreitung der Justinianischen Pest in den 540er Jahren (gelb) auf einem farbigen Voronoi-Diagramm der räumlichen Verteilung von Closeness-Werten der Knoten im ORBIS-Netzwerk-Modell für das Römische Reich*

Data/Daten: http://orbis.stanford.edu/ and Harper 2017; calculations and map: *J. Preiser-Kapeller*

Robustness and fragmentation of imperial networks

As discussed above, complex networks are not uniformly connected; we have observed major differences in centrality measures between nodes. Equally, networks are often structured in clusters, i.e. groups of nodes that are more densely and closely connected among each other than with the rest of the network; they may be identified as 'sub-communities' within the larger system. For their identification, one can use algorithms for 'group detection', such as the algorithm developed by the physicist *M. Newman* (2010, pp. 372–382), which aims at an 'optimal' partition of the network into clusters. Complex networks are also characterised by 'nested clustering', i.e. within clusters further sub-clusters can be detected, within which yet further cluster can be identified, across several levels of hierarchy (*Barabási* 2016, pp. 331–338).

For the ORBIS model, with the help of the Newman algorithm, we identified 25 supra-regional clusters of higher internal connectivity (see table 5 and fig. 15). Most of these clusters owe their connectivity to either maritime connections (nos.

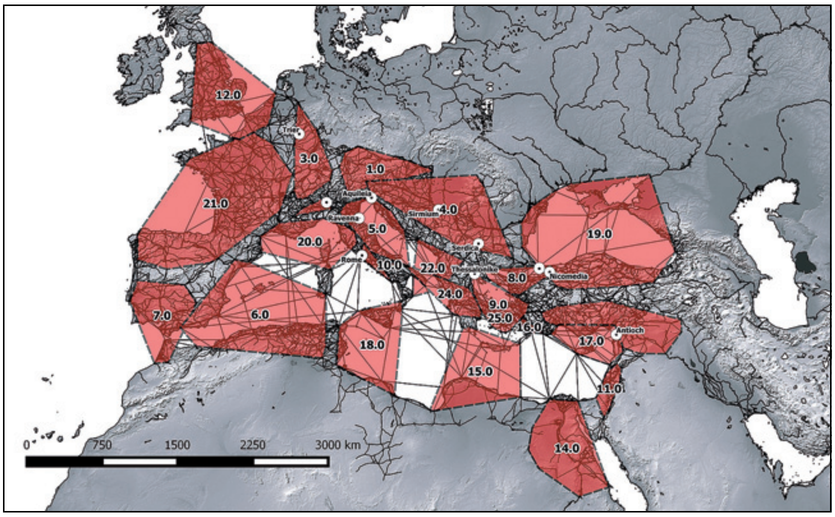

Fig. 15: *25 supra-regional clusters identified among nodes in the ORBIS network model for the Roman Empire with the help of the Newman algorithm*

Abb. 15: *25 überregionale Cluster, die unter den Knoten im ORBIS-Netzwerk-Modell für das Römische Reich mithilfe eines Newman-Algorithmus bestimmt worden sind*

Data/Daten: http://orbis.stanford.edu/; calculations and map: *J. Preiser-Kapeller*

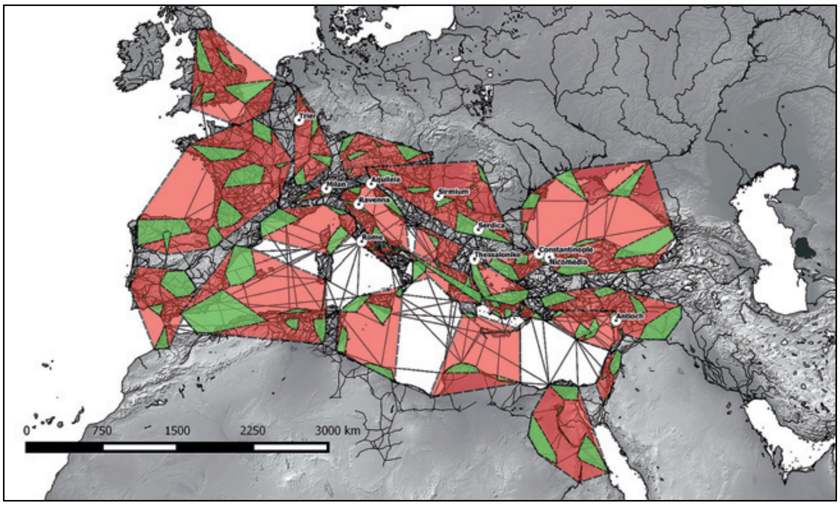

Fig. 16: *Regional clusters (green) identified in the 25 supra-regional clusters (red) identified among nodes in the ORBIS network model for the Roman Empire with the help of the Newman algorithm*

Abb. 16: *Regionale Cluster (grün), die in den 25 überregionalen Clustern (rot) unter den Knoten im ORBIS-Netzwerk-Modell für das Römische Reich mithilfe eines Newman-Algorithmus bestimmt worden sind*

Data/Daten: http://orbis.stanford.edu/; calculations and map: *J. Preiser-Kapeller*

5, 6, 7, 8, 9, 12, 13, 15, 16, 17, 18, 19, 20, 21, 22, 24, 25) or riverine routes (nos. 1, 3, 4, 14, 23) (see also *McCormick* 2001, pp. 77–114). In order to test the concept of 'nested clustering', we also applied the Newman algorithm on each of the 25 (supra)regional clusters of the ORBIS network, resulting in the identification of between three and eight regional sub-clusters within each of the larger clusters (see fig. 16). We may therefore perceive this complex network model of localities and routes in the Roman Empire across several spatial scales as a system of nested clusters, down to the level of individual settlements and their hinterlands (on the Mediterranean as 'agglomeration' of micro-regions and the role of (imperial) connectivity see also *Horden* and *Purcell* 2000; *Manning* 2018). In such a network, the speed and cohesion of empire-wide connectivity depends on the trans-regional links between these clusters, which structure the entire system.

Table 5: Regional attributions of clusters of nodes in the ORBIS network model identified with the help of the Newman algorithm

Tab. 5: Regionale Zuordnung von Clustern von Knoten im ORBIS-Netzwerk-Modell, die mithilfe eines Newman-Algorithmus bestimmt worden sind

Newman cluster no.	**Regions of the Roman Empire**
1	Upper Danube, eastern Alps
2	Northern Syria, north-western Mesopotamia, southern Asia Minor
3	Rhine area
4	Middle Danube, northern Balkans
5	Northern and central Adriatic
6	Central North Africa, East coast of the Iberian Peninsula, Baleares
7	Southern Iberian Peninsula, western North Africa
8	Region around the Sea of Marmara, northern Aegean
9	Central and north-western Aegean
10	Central southern Italy
11	Palestine
12	Britannia and Channel coast
13	Rome, Latium and Campania
14	Egypt
15	Cyrenaica, Crete and southern Peloponnese
16	South-western Asia Minor
17	Cyprus and northern coasts of the Levant
18	Eastern North Africa, Sicily and south-western South Italy
19	Black Sea and North of Asia Minor

Newman cluster no.	Regions of the Roman Empire
20	Etruria, Liguria, Corsica and south-eastern Gaul
21	Gaul and North of the Iberian Peninsula
22	Southern Adriatic and northern Epirus
23	Western plain of the river Po
24	North-western central Greece, northern Peloponnese and Ionian Sea
25	Central Aegean (micro-cluster)

A similar picture emerges if we apply the same Newman clustering algorithm to the network model for China (see table 6 and fig. 17). Especially the major clusters (such as nos. 1, 10, 14, 19, 23) emerge based on riverine connectivity, while the largest cluster, no. 3 (see fig. 17), connects the places along the Grand Canal network (it also includes the four ancient capitals of Luoyang, Kaifeng, Nanjing and Hangzhou). These especially 'hydrous', supra-regional linkages (as in the Roman case) allow for a cohesion of the imperial network at large and its integration of macro- and micro-regions into one overarching system (for the actual regional structure of imperial China cf. also *Mostern* 2011).

Table 6: Regional attributions of clusters of nodes in the China network model identified with the help of the Newman algorithm

Tab. 6: Regionale Zuordnung von Clustern von Knoten im China-Netzwerk-Modell, die mithilfe eines Newman-Algorithmus bestimmt worden sind

Newman cluster no.	Regions and provinces of present-day China
1	Shaanxi province with the ancient capital of Chang'an
2	Hebei province and the Beijing area
3	The regions along the Grand Canals from Hangzhou to Hebei
4	The east of Guangdong province
5	Parts of Anhui and Jiangxi provinces
6	Parts of Liaoning province
7	The west of Guangdong and parts of Hunan province
8	Shandong province
9	Fujian province
10	The central core between Chang'an in the north and Hunan in the south
11	Coastal parts of Zhejiang province
12	Parts of Sichuan province

Newman cluster no.	Regions and provinces of present-day China
13	Guangxi province
14	Parts of Sichuan and Chongqing provinces
15	Guizhou province
16	Eastern parts of Gansu province
17	Main parts of Gansu province
18	Southernmost parts of Guangdong province
19	Yunnan province (major part) and adjacent regions
20	Shanxi province
21	Micro-cluster in western Guangxi province
22	Westernmost parts of Yunnan province
23	Jiangxi province and adjacent areas
24	Ningxia province
25	Southernmost parts of Sichuan province
26	Easternmost parts of Yunnan province

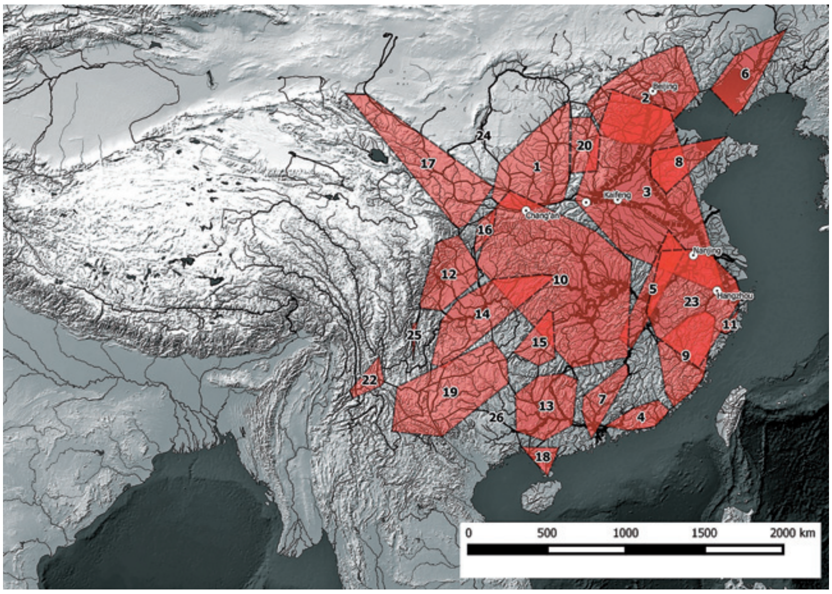

Fig. 17: *26 supra-regional clusters identified among nodes in the network model for Imperial China with the help of the Newman algorithm*

Abb. 17: *26 überregionale Cluster, die unter den Knoten im Netzwerk-Modell für das Chinesische Reich mithilfe eines Newman-Algorithmus bestimmt worden sind*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

The results of the Newman clustering algorithm, however, are only one of various possible solutions to the problem of community detection. Different clustering algorithms will produce different attributions of nodes into clusters, such as the Louvain algorithm, which we also applied to both network models (for an example, see fig. 18). Even the same Newman algorithm will suggest a different partition into clusters of the same network if some parameters (such as relative link weights of land, riverine and maritime connections) are modified. Yet, all the results obtained for the two network models show the same pattern of nested clusters from the supra-regional down to the local level, following the same 'logics' of increased connectivity (trans-maritime linkages in the Roman case, for instance) (*Newman* 2010, pp. 354–392; *Estrada* 2012, pp. 187–213; *Barabási* 2016, pp. 320–362).

Could these boundaries between clusters also work as potential rupture lines in case of a weakening of the network´s cohesion? The robustness or vulnerability of complex networks has attracted a considerable amount of attention, not least due to the relevance of these questions for present-day infrastructural webs. As *Ginestra Bianconi* (2018, pp. 49–57) has stated, *"it is assumed that a fundamental proxy for the proper function of a given network is the existence of a giant component, […] which allows the propagation of ideas, information and signals"* as well as resources and people across (most of) the network. The extent to which such as giant component within a given network exists is indicated by the so-called 'percolation threshold', which allows for the existence of large clusters and long-range connectivity. Below this threshold, a network disintegrates into various components of smaller size, and system-wide connectivity is severely damaged (see also *Wang* and *Ducruet* 2013). One test of a network´s robustness is the successive removal of nodes, *"monitoring the fraction of nodes that remains in the giant component of the network after the inflicted damage"*, thus *"simulating"* a cascading failure or destruction of nodes. The removal of nodes can be executed randomly or in the form of a *"targeted attack"*, when nodes are damaged *"according to a non-random strategy"* such as selecting nodes which rank high in certain centrality measures. Characteristically, large-scale complex networks would be very robust vis-à-vis random attacks, since, due to the inequality in the distribution of centrality values (see fig. 1 and fig. 2), there is a high probability that only peripheral nodes are affected while the central hubs remain intact. A targeted attack on the latter, however, could lead to a rapid fragmentation of the network (*Bianconi* 2018, pp. 49–57). We used the targeted attack approach and successively removed the nodes ranking topmost in betweenness centrality until a considerable share (at least 20 %) of the network was no longer connected to the original giant component.

Both network models show a significant robustness even towards such a 'non-random strategy': in the ORBIS network, we removed the top 50 nodes in betweenness (that is 7.3 % of all nodes of the unmodified network) before we observed a major disruption (see fig. 19). Interestingly, after this rupture, the north-western regions of the network emerge as a separate component (no. 1, in green), while the entire Mediterranean area is integrated in one (still relatively giant)

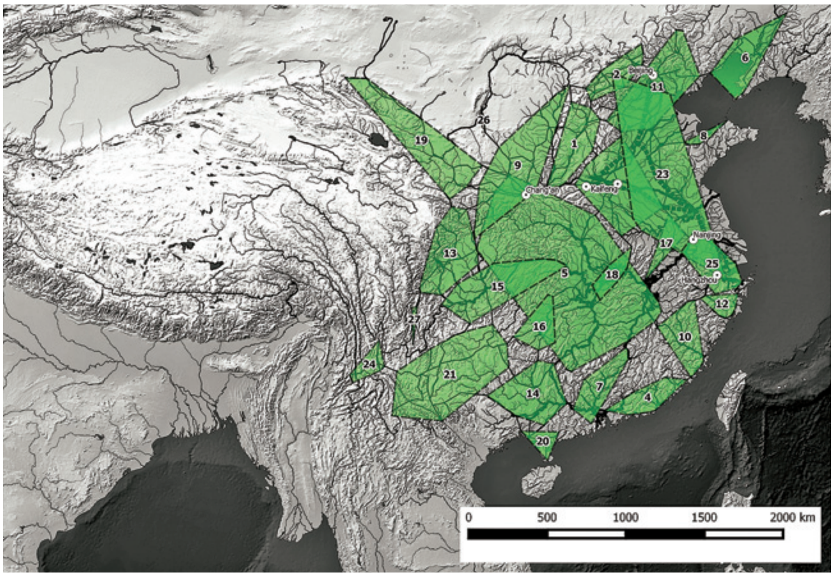

Fig. 18: *27 supra-regional clusters identified among nodes in the network model for Imperial China with the help of the Louvain algorithm*

Abb. 18: *27 überregionale Cluster, die unter den Knoten im Netzwerk-Modell für das Chinesische Reich mithilfe eines Louvain-Algorithmus bestimmt worden sind*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

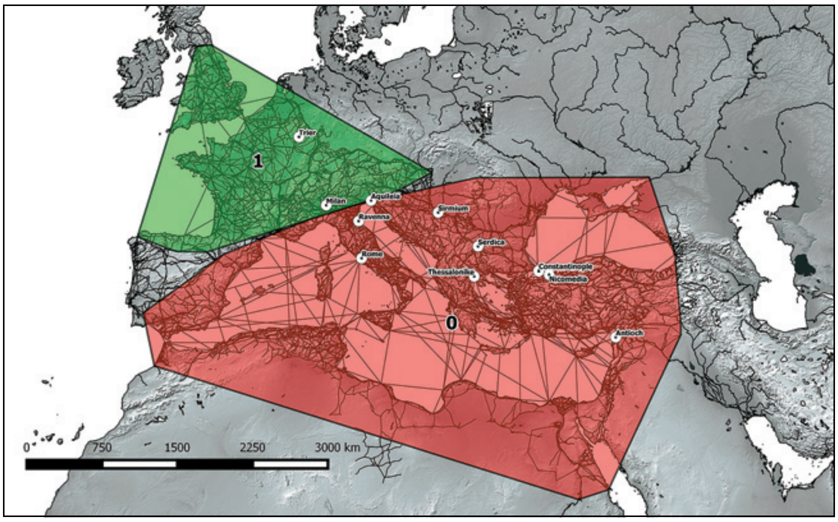

Fig. 19: *Fragmentation of the ORBIS network model for the Roman Empire in two components after the removal of the top 50 nodes in betweenness values*

Abb. 19: *Fragmentierung des ORBIS-Netzwerk-Modells für das Römische Reich in zwei Teile nach Entfernung der 50 hochwertigsten Knoten der »Betweenness«-Werte*

Data/Daten: http://orbis.stanford.edu/; calculations and map: *J. Preiser-Kapeller*

component (no. 2, in red) (see fig. 19). This again highlights the significance of maritime connectivity for the network´s cohesion, but could (very tentatively) also be connected to post–476 CE scenarios involving an attempt at renewing Mediterranean imperial unity by Emperor *Justinian* in the 6th century CE or the (now out-dated) '*Pirenne* thesis' about the emancipation of the Frankish Empire from the Mediterranean core (*Preiser-Kapeller* 2018).

The China network proves to be even more robust to targeted node failure. Only after removing the 150 top nodes in betweenness (14.5 % of all nodes of the unmodified network) did smaller separate components emerge in the North-east (no. 2), the North-west (no. 7) and especially the South (no. 4), while the core at large remains intact (component no. 1, in orange), including all traditional imperial capitals (see fig. 20). Again, we attribute this to the cohesive effect of the riverine connections, augmented by large-scale imperial infrastructural projects such as the Grand Canal.

Yet, what happens, if these relatively cost-intensive, perhaps even *"fragile links"* across larger distances, as *Ward-Perkins* (2006, p. 382) has called them for the Roman Empire, *"disappear"*? In order to answer this question, we applied another robustness test and eliminated step by step all links from the network models above a specific 'cost' threshold; this could be interpreted as a 'simulation' of the dwindling ability of an imperial centre to maintain (or defend) expensive and vulnerable long-distance connections and infrastructures.

For the ORBIS network, we successively removed all links which would 'cost' more than five, more than three, more than two and finally more than one day´s journey(s) (according to the calculations of the ORBIS team) (see table 1). The result is an increasing fragmentation of the network in components of different size, partially along the 'rupture lines' between the clusters and sub-clusters, which we identified for the unmodified network model (see above). But even if we eliminate the connections across longer distances, some larger, supra-regional clusters, again especially of maritime connectivity, demonstrate remarkable robustness (see also *McCormick* 2001, pp. 565–569, on the resilience of certain sea routes in the 7th to 9th centuries CE). In the model, in which all connections that 'cost' more than one day´s journey are deleted (see table 1 and fig. 21), the largest still fully connected component (no. 6, in yellow) is located in the Eastern Mediterranean between the Tyrrhenian Sea and the Levant, with its centre in the Aegean. This would correspond to the central regions and communication routes, which remained under control of the (Eastern) Roman Empire after the loss of its eastern provinces to the Arabs in the 7th century CE, at the end of an actual process of increasing fragmentation of the (post-)Roman world (*Brubaker* and *Haldon* 2011; *Vaccaro* 2013; *Haldon* 2016). We applied the Newman algorithm in turn to this remaining largest component (no. 6) and identified again various regional clusters nested within the larger connected system, especially in the Aegean and along the coasts of Asia Minor. Interestingly, the (former) imperial residences of Rome and Ravenna also have resilient medium-sized components intact in this scenario (see fig. 22). Yet, besides the resilience of maritime connectivity in regions of Italy and the Eastern Mediterranean (and equally an uninterrupted co-

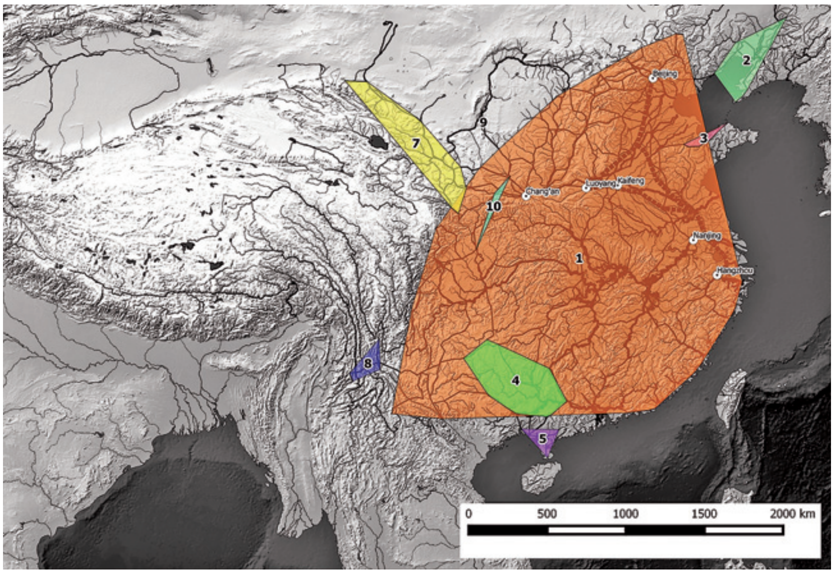

Fig. 20: *Fragmentation of the network model for Imperial China in various components after the removal of the top 150 nodes in betweenness values*

Abb. 20: *Fragmentierung des Netzwerk-Modells für das Chinesische Reich in verschiedene Teile nach Entfernung der 150 hochwertigsten Knoten der »Betweenness«-Werte*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

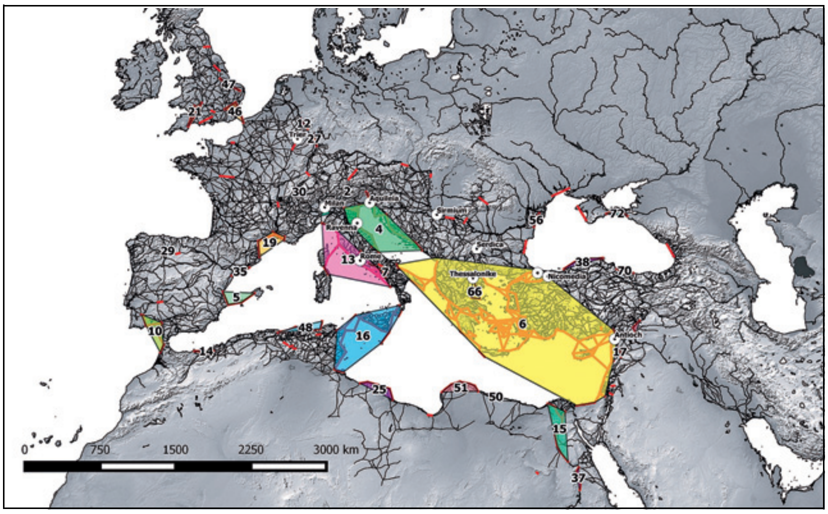

Fig. 21: *Fragmentation of the ORBIS network model for the Roman Empire in various components after the removal of all links beyond a cost-threshold of one day of travel*

Abb. 21: *Fragmentierung des ORBIS-Netzwerk-Modells für das Römische Reich in verschiedene Teile nach Entfernung aller Kanten über einem Kostenschwellenwert eines Reisetages*

Data/Daten: http://orbis.stanford.edu/; calculations and map: *J. Preiser-Kapeller*

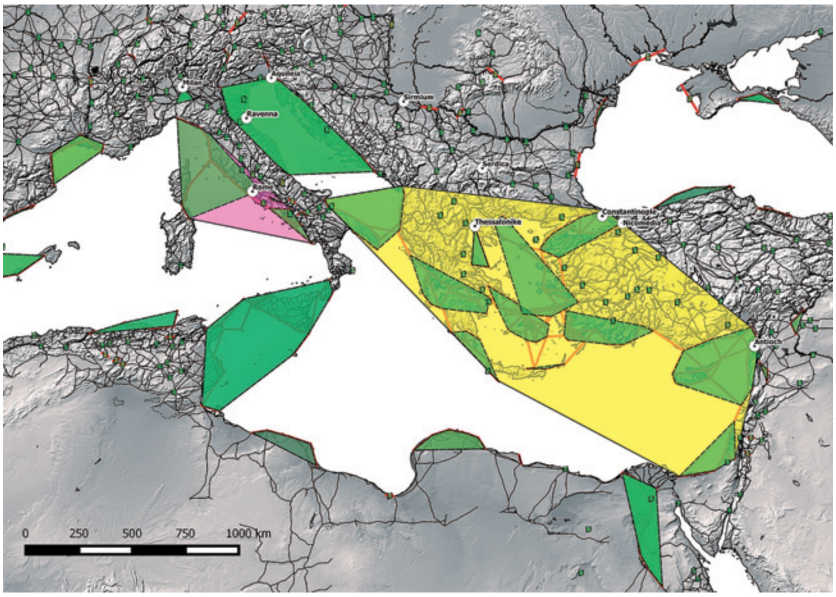

Fig. 22: Fragmentation of the ORBIS network model for the Roman Empire in various components after the removal of all links beyond a cost-threshold of one day of travel and identification of regional clusters (in green) within these components with the help of the Newman algorithm

Abb. 22: Fragmentierung des ORBIS-Netzwerk-Modells für das Römische Reich in verschiedene Teile nach Entfernung aller Kanten über einen Kostenschwellenwert eines Reisetages und Bestimmung von regionalen Clustern (grün) innerhalb dieser Gruppierungen mithilfe eines Newman-Algorithmus

Data/Daten: http://orbis.stanford.edu/; calculations and map: *J. Preiser-Kapeller*

hesion of the 'Egyptian' cluster, see also *Wickham* 2005, pp. 759–769), we observe a general 'disentanglement' of large parts of the Roman traffic system, especially in the western part of Europe, in the interior of the Balkans or between the northern and southern coasts of the Mediterranean (see table 1 and fig. 21). Of course, the model is at best an approximation towards certain structural parameters of the web of transport links within the Imperium Romanum. Nevertheless, we observe some remarkable parallels to actual historical processes of the 5^{th} to 7^{th} centuries CE (*Wickham* 2004 for instance wrote about a partial 'micro-regionalisation' of the 'Mediterranean world-system' during this period), which hint at the impact of processes of integration, respectively disentanglement, especially due to the establishment and growth respectively the contraction of long-distance connections (*McCormick* 2001, pp. 270–277, 385–387).

We conducted the same test on the China network model, removing all links, which would 'cost' more than five, more than three, more than two and finally more than one day´s journey(s) (see table 2). In this case, a major impact on the connectedness can be observed after the removal of all links 'worth' more than

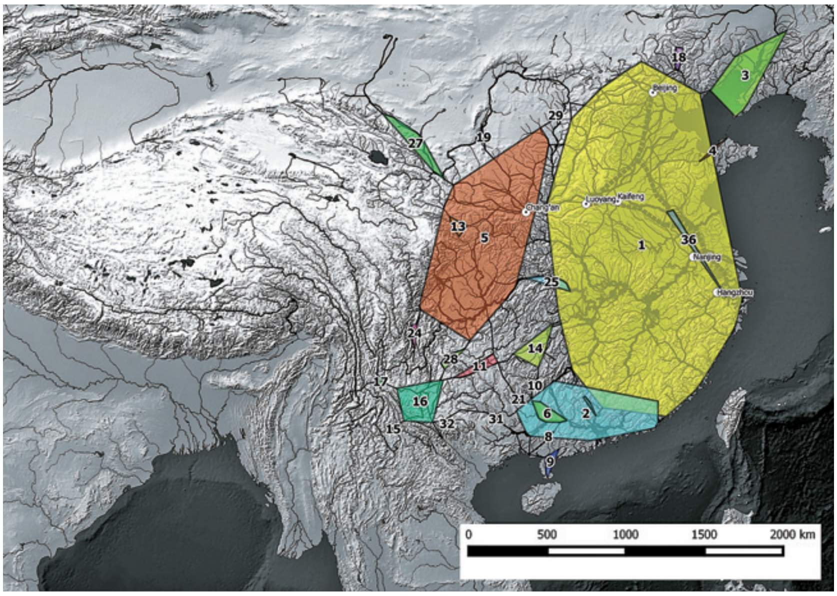

Fig. 23: *Fragmentation of the network model for Imperial China in various components after the removal of all links beyond a cost-threshold of two days of travel*

Abb. 23: *Fragmentierung des Netzwerk-Modells für das Chinesische Reich in verschiedene Teile nach Entfernung aller Kanten über einem Kostenschwellenwert von zwei Reisetagen*

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

two days of travel (see fig. 23), with smaller components emerging in the West (no. 5, with Chang´an), North-West (no. 27), North-East (no. 3), South (no. 2) and South-West (no. 16) (on actual regional faults in Chinese history cf. *Schmidt-Glintzer* 1997). Still, one major component covers the entire eastern part of the network, including the central region along the Grand Canal(s) with the capitals of Beijing, Luoyang, Kaifeng, Nanjing and Hangzhou and ranging all the way to the South as far as Fujian province (with a total of 478 nodes or 46 % of the unmodified network) (see fig. 23). The next step, i.e. the elimination of all links 'costing' more than one day's journey, however results in a total fragmentation of the model, with a multitude of small-scale networks, none containing more than 20 nodes (or 0.02 % of the original network) (see table 2 and fig. 24). In contrast to the ORBIS model, no resilient larger component emerges after this robustness test. This may indicate that from a structural point of view imperial cohesion over larger territories in China came at a greater cost than in the Mediterranean, maritime-based network. Against such a scenario, the relative endurance of unified imperial regimes in China compared to the more fragmented (and after the 5th century CE never again entirely politically integrated) Mediterranean is even more remarkable (cf. also *Schmidt-Glintzer* 1997; *Scheidel* 2009).

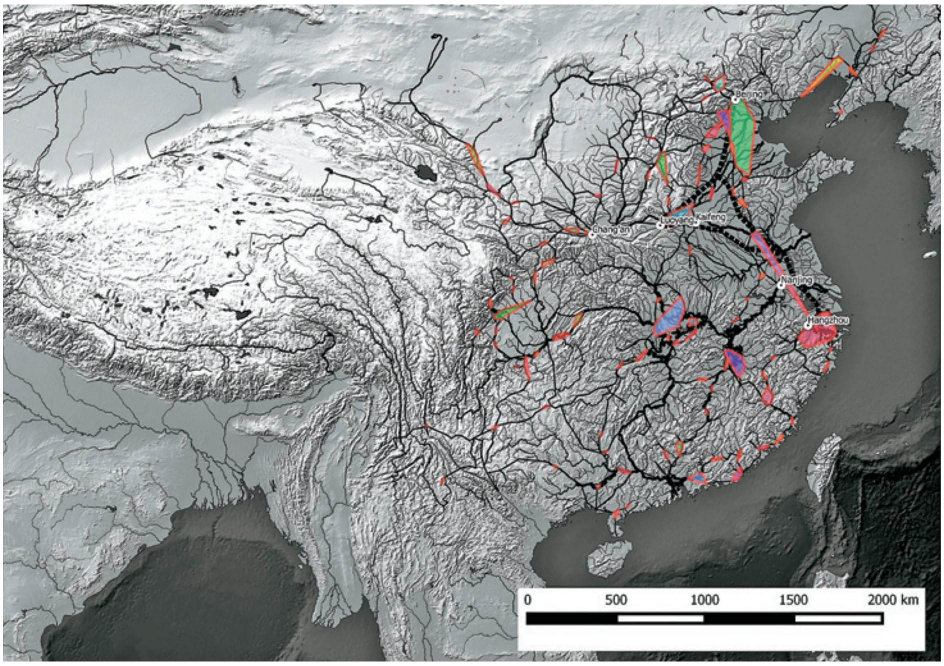

Fig. 24: Fragmentation of the network model for Imperial China in various components after the removal of all links beyond a cost-threshold of one day of travel

Abb. 24: Fragmentierung des Netzwerk-Modells für das Chinesische Reich in verschiedene Teile nach Entfernung aller Kanten über einem Kostenschwellenwert eines Reisetages

Data/Daten: http://sites.fas.harvard.edu/~chgis/; calculations and map: *J. Preiser-Kapeller*

Conclusion

The very different historical trajectories of the Euro-Mediterranean region and of China invalidate any deterministic interpretation of a structural-quantitative approach to empires of the past (see also *Scheidel* 2009). Although some recent studies suggest a long-term impact of the imperial infrastructures of Rome or ancient China even on modern-day economic performance (*Fang, Feinman* and *Nicholas* 2015; *Dalgaard, Kaarsen, Olsson* and *Selaya* 2018), understanding them as complex networks leads to an expectation of a high diversity of responses to internal dynamics and external challenges, especially across spatial scales. Remarkable resilience at the regional level can coexist with the disintegration of the system at large; the multitude of developments in the 'post-Roman' world, as highlighted in recent research (*Cameron, Ward-Perkins* and *Whitby* 2000; *Sarris* 2011; *Demandt* 2015; *Preiser-Kapeller* 2016), would be in keeping with such 'complex behaviour'. Equally, in the Chinese case, imperial unity was no 'frozen evolutionary path', as periods of political multiplicity in the 4th–6th centuries, the 10th century or the first half of the 20th century CE after the fall of the Ch'ing dynasty indicate (*Elvin* 1973; *Huang* 1988). On the other hand, China could also serve as an example of the relative robustness of large-scale imperial networks at large under changing regimes and after episodes of fragmentation. The establishment of the Grand Canal network also initiated a certain 'path dependence' with regard to the selection of 'nodes' as centres of the imperial system. When it comes to network analytical measures, Chinese rulers were rather 'successful' in their decision-making, if we follow *F.W. Carter* again. Based on our findings, we may confirm his verdict and conclude with him that *"there therefore seems little excuse why the historical geographer should not attempt to use some of these techniques in his analysis of certain aspects of the past."* (*Carter* 1969, p. 46)

Summary

This study proposes to proceed from a rather metaphorical application of network terminology on polities and imperial formations of the past to an actual use of tools and concepts of network science. For this purpose, a well-established network model of the route system in the Roman Empire (ORBIS) and a newly created network model of the infrastructural web of Imperial China are visualised and analysed with regard to their structural properties. Findings indicate that these systems could be understood as large-scale complex networks with pronounced differences in centrality and connectivity among places and a hierarchical sequence of clusters across spatial scales from the supra-regional to the local level. Such properties in turn would influence the cohesion and robustness of imperial networks, as is demonstrated by two tests on the model´s vulnerability to node failure and to the collapse of long-distance connectivity. Tentatively, results can be connected to actual historical dynamics and thus hint at underlying network mechanisms of large-scale integration and disintegration of political formations.

Zusammenfassung

Netzwerke und Resilienz sowie der Untergang von Imperien
Ein Makro-Vergleich des Imperium Romanum und des chinesischen Kaiserreichs

In diesem Beitrag wird eine nicht-metaphorische Anwendung des Netzwerkbegriffes für die Erfassung vergangener politischer und imperialer Systeme mit den Techniken und Konzepten der Netzwerktheorien vorgeschlagen. Dazu werden das bekannte Modell für das Straßensystem im Römischen Reich (ORBIS) und ein neu entwickeltes Netzwerk-Modell für die Infrastruktur im Chinesischen Reich hinsichtlich ihrer strukturellen Merkmale visualisiert und analysiert. Die Ergebnisse lassen darauf schließen, dass diese Systeme umfangreiche, komplexe Netzwerke darstellen, die sich deutlich in ihrer Zentralität und Konnektivität zwischen einzelnen Orten unterscheiden, und die eine hierarchische Anordnung von Clustern über verschiedene räumliche (überregionale bis lokale) Stufen erkennen

lassen. Diese Merkmale könnten wiederum den Zusammenhalt und die Widerstandsfähigkeit imperialer Netzwerke beeinflussen, wie zwei Beispiele verdeutichen, die die Anfälligkeit des Modells beim Wegfall von Knotenpunkten und von Fernverbindungen zeigen. Diese Ergebnisse lassen sich vorläufig mit tatsächlichen historischen Dynamiken verknüpfen, die Hinweise für Netzwerkmechanismen liefern, denen großflächige Integration oder Zerfall politischer Formationen zugrunde liegen.

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