CESifo WORKING PAPERS

7740
2019

July 2019

Roman Transport Network Connectivity and Economic Integration

Matthias Flückiger, Erik Hornung, Mario Larch, Markus Ludwig, Allard Mees

CESifo

Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editor: Clemens Fuest
www.cesifo-group.org/wp

CESifo *Working Paper No. 7740*
Category 8: Trade Policy

Roman Transport Network Connectivity and Economic Integration

Abstract

We show that the creation of the first integrated pan-European transport network during Roman times influences economic integration over two millennia. Drawing on spatially highly disaggregated data on excavated Roman ceramics, we document that interregional trade was strongly influenced by connectivity within the network. Today, these connectivity differentials continue to influence cross-regional firm investment behaviour. Continuity is largely explained by selective infrastructure routing and cultural integration due to bilateral convergence in preferences and values. Both plausibly arise from network-induced history of repeated socio-economic interaction. We show that our results are Roman-connectivity specific and do not reflect pre-existing patterns of exchange.

JEL-Codes: F140, F150, F210, N730, R120, R400, O180.

Keywords: economic integration, Roman trade, transport network connectivity, business links, cultural similarity.

Matthias Flückiger
Queen's University Belfast / Northern Ireland
matthias.flueckiger@qub.ac.uk

Erik Hornung
University of Cologne / Germany
hornung@wiso.uni-koeln.de

Mario Larch
University of Bayreuth / Germany
mario.larch@uni-bayreuth.de

Markus Ludwig
University of Bayreuth / Germany
markus.ludwig@uni-bayreuth.de

Allard Mees
Romano-Germanic Central Museum
Mainz / Germany
mees@rgzm.de

This version: July 2019
We thank Alina Bartscher, Michael Burda, Sebastian Braun, Alan de Bromhead, José De Sousa, Hartmut Egger, Richard Franke, David Jacks, Miren Lafourcade, Claire Lelarge, Stephan Maurer, Eric Melander, Luigi Pascali, Fabian Wahl, Niko Wolf, and seminar participants at Bayreuth, HU Berlin, Bonn, TU Braunschweig, Cologne, George Mason, Hamburg, Konstanz, Paris-Sud, WU Vienna, the 2nd Workshop on Geodata and Economics in Hamburg, and the Canadian Economics Association Annual Meeting 2019 for excellent feedback. We are grateful to Ömer Özak for kindly sharing data on the Human Mobility Index and Rome2rio.com for providing us with data on travel times. We also thank Lukas Diebold, Oliver Parker, and Leandro Navarro for excellent research assistance. We declare that we have no relevant or material financial interests that relate to the research described in this paper.

1 Introduction

Large-scale transport infrastructure projects shape connectivity patterns and determine the distribution of economic activity across space by altering the physical costs of exchange. Changes in connectivity may have long-lasting consequences for connected regions because repeated interactions reduce information frictions and increase cultural integration. While many studies investigate the effects of changing trade costs and transport infrastructure on the local level of integration, we know surprisingly little about the potential origins of systematic differences in bilateral transport connectivity and information frictions between regions. One of the largest infrastructure projects in history, the Belt and Road initiative, to a large degree traces the ancient Silk Road along which goods, ideas, and cultural values have been exchanged over millennia. If new infrastructure projects follow existing patterns of economic integration, transport costs as well as informal barriers to integration—such as cultural differences—may be influenced by historical economic integration. Hence, policy makers and economists need to be aware of the history of bilateral exchange and the concurrent integration of attitudes and tastes when evaluating the welfare effects of infrastructure projects and regional policies and when discussing the optimal allocation of infrastructure resources.

This paper argues that the first pan-European multi-modal transport network, which was created during ancient Roman times, had fundamental and lasting effects on the intensity of interregional (socio-)economic exchange. The unprecedented reach of the integrated network, combined with technological and institutional progress, dramatically reduced transport costs and changed the pattern of interregional trade in ancient Western Europe. In the absence of substantial change in transport technologies until the transportation revolution of the 19th century, better connected regions within the Roman transport network continued to experience more intensive exchange for centuries. The long history of more intense repeated (socio-)economic interaction led to the convergence of preferences and values and thereby reduced information frictions, potentially reinforcing the intensity of exchange. By increasing cultural similarity and reducing information asymmetries, important determinants of cross-regional capital flows, Roman transport connectivity influences the spatial pattern of firm ownership today. Based on the arguments outlined above, we derive the testable hypotheses that variation in connectivity within the Roman transport network determined historical trade flows and influences the intensity of cross-regional firm ownership today via its similarity-increasing effect on economic and cultural aspects.

To empirically investigate these hypotheses, we create a dataset of Western European regions, defined as grid cells (0.5×0.5 degrees), for which we trace the history of bilateral (socio-)economic exchange over two millennia.[1] For each pair of grid cells, we determine the level of connectivity within the multi-modal Roman transport network. This network is a collection of numerous segments—representing sections of sea, river, or road—which differ in length and associated mode of transport. Based on Diocletian's Edict on Prices of 301 CE, a contemporary and widely used source, we determine Roman-technology-driven differences in freight

---

[1] In the remainder of this paper, we will use the terms 'grid cell' and 'region' interchangeably.

rates across transport modes. Using this information, we identify the least-cost path between any two grid cells that are connected to the network. The costs associated with shipping goods along this optimal path within the network (referred to as *effective* distance) constitute our measure of connectivity that is specific to the Roman era.[2]

In the first step of our analysis, we investigate whether variation in effective distance influenced the intensity of trade during Roman times. To this end, we draw on geocoded information for more than 246,000 excavated potsherds of Roman fine tableware collected in the hitherto underexploited Samian Research database (Römisch-Germanisches Zentralmuseum in Mainz). A unique feature of the mass-produced and widely used ceramic tableware—subsequently referred to as 'terra sigillata'—is that production sites (i.e., the origins of the tableware) are clearly identifiable. Combined with precise information on the location of archaeological excavation sites (i.e., the destination of the terra sigillata), this allows us to aggregate the number of finds to the grid-cell-pair level and capture interregional trade volumes within Western Europe during the Roman era. The possibility to trace terra sigillata from origin to destination, combined with the fact that they were traded throughout the entire Roman territory, makes them ideal goods to study the emergence of long-distance trade in the first European-wide integrated market.

To empirically estimate the relationship between historical trade volumes and effective distance, we employ an empirical approach in which we control for any local time-invariant heterogeneity by including origin and destination fixed effects. This considerably assuages concerns related to excavation biases or endogenous routing of roads.[3] The regression results document that effective distance strongly influenced the volume of interregional trade. A one percent increase in effective distance reduces trade by 2.4%. This elasticity is close to estimates for other historical periods.[4] Compared to studies using modern trade data, effective distance seems to have had a somewhat stronger trade-deterrent effect during Roman times.[5] This is consistent with expectations and the notion of increased globalisation.

We use narrative and econometric evidence to support the argument that our findings are specifically attributable to the creation of the Roman transport network and the resulting change in connectivity across regions. A particularly pressing concern is that the expansion of transport infrastructure was endogenous to pre-existing cultural and economic exchange. In this case, connectivity within the network would (partly) reflect existing patterns of socio-economic exchange and, consequently, bias our estimates. To alleviate this concern, we survey

---

[2] To isolate the Roman-era-specific part of the transport network effect, we control for Euclidean distance throughout our empirical analysis.

[3] Note that endogeneity in placement of roads does not constitute a threat to identification. The fact that grid cells may be intersected by (multiple) roads is absorbed by the origin and destination fixed effects. Furthermore, since we only include grid cells that are intersected by at least one segment of the Roman transport network, we focus on the intensive margin of connectivity. In the context of our study, concerns related to endogeneity (only) pertain to bilateral aspects that systematically influence the routing of the network.

[4] Donaldson (2018) estimates an *effective distance* elasticity of -1.603 for Northern India during 1861–1930. In his study, the transport network also incorporates the newly introduced railway. Barjamovic et al. (forthcoming) estimate a *geographic distance* elasticity of -1.912 for cities during the Bronze Age. Wolf (2009) estimates an elasticity of -1.603 when looking at the effect of *geographic distance* on trade volumes across trade districts in central Europe during the period 1885–1933.

[5] In a meta-analysis of 2,508 estimates obtained from 159 papers, Head and Mayer (2014) report a mean *geographic distance* elasticity of -0.89 across all gravity estimates and of -1.1 when focusing on structural gravity estimates alone.

the historical literature and show that historians of the antiquity are overwhelmingly of the view that the Romans designed their transport network, including roads, bridges, and canals, predominantly to serve military purposes and disregarded local conditions (see, e.g., Temin, 2012; Laurence, 2002; Davies, 1998). Additionally, we provide quantitative evidence showing that effective distance does not explain pre-existing interregional patterns of socio-economic integration, measured by the diffusion of burial traditions during the Neolithic and Bronze Age, as well as settlement patterns in the Iron Age. To address the possibility that least cost paths within the Roman transport network simply follow geographically optimal paths, we control for a variety of geography-based least cost-path measures. Conditional on Euclidean distance, our results remain qualitatively unchanged, supporting the view that geographical features did not play the dominant role in the routing decisions of Roman engineers.

In the second step of our analysis, we provide evidence that Roman-era-specific transport network connectivity continued to influence the geography of trade until the advent of steam power and new transport technologies during the Industrial Revolution. Specifically, we show that effective distance is associated with greater interregional market integration, proxied by commodity price correlations between 1321–1790 and the transmission speed of the Black Death in the period 1347–51. These results are consistent with a continuous use of, and repeated investment in, the Roman transport technology and support the hypothesis that regions better connected within the network continued to trade and interact more intensively over a period of almost two millennia.

In the third step of our analysis, we document that differential connectivity within the Roman network is reflected in the spatial pattern of firm ownership today, despite the fundamental changes in relative transport costs that occurred since the advent of railways and air travel. Drawing on geocoded firm-level data from the Bureau van Dijk's Orbis database, we show that better connectivity increases the number of cross-regional parent-subsidiary connections. A one percent increase in effective distance reduces ownership connections by 0.55%. This finding highlights that today's pattern of bilateral economic integration in Western Europe is (partly) determined by infrastructure investments undertaken 2,000 years ago. To substantiate the Roman-era-specificity of our results, we exploit the fact that economic and institutional integration within the Roman Empire discontinuously changed at the Limes Germanicus. This north-eastern line of defence was primarily built for military purposes but proved useful to monitor and control cross-border trade and information flows between the Roman Empire and the 'barbarian' world. Importantly, the Roman transport network did not extend across this border. Consistent with our argument that integration into the Roman trade network influences today's spatial ownership patterns, we find significantly fewer ties between firms *across* the vanished borderline than *within* either side. To further support the validity of our results, we conduct a battery of robustness tests, including conditioning on geography-based least-cost path measures.

Motivated by Cravino and Levchenko (2017)'s work documenting that foreign direct investment is an important transmission channel of business cycles, we extend our analysis to investigate whether the Roman connectivity effect on firm ownership is also reflected in business cycle integration. Using correlation in night-time luminosity growth as proxy for integration, we find that synchronisation increases with greater connectivity. This result corroborates that ancient transport network connectivity influences economic integration today.

In the final step of our analysis, we investigate potential mechanisms that link variation in connectivity within the ancient transport network to cross-regional firm investment behaviour today. Guided by recent studies (discussed below), we focus on two mechanisms: persistence in transport infrastructure connectivity and cultural convergence due to repeated interactions. Both of these channels can reduce information frictions, thereby facilitating cross-regional investment. We first show that regions better connected within the Roman transport network continue to be more closely linked within today's transport network. The intertemporal correlation of infrastructure connectivity can explain a substantial part (50%) of the Roman-era-specific effect on cross-regional firm ownership. This does not seem to be driven by a replication of the structure of the transport network. Rather, our results suggest that regions with stronger ancient connectivity were connected more directly when new transport technologies (e.g., railways, aeroplanes, and highways) became available and old technologies (e.g., river transport) became less relevant. Thus, even though past and present transport networks differ in their layout and transport technologies, Roman-era-specific connectivity still explains patterns of today's bilateral connectivity. Second, we show that the effect of Roman-transport-network connectivity works through cultural similarity. A larger effective distance is associated with a lower degree of similarity in preferences and values as reported in the Global Preferences Survey (GPS, Falk et al., 2018) and the European Values Study (EVS, EVS, 2016). This implies that the cumulative history of exchange within the Roman-transport-network resulted in a convergence in preference and values. Cultural integration, a fundamental determinant of economic interaction, accounts for 34% of the Roman-transport-network effect on firm ownership. Combined, the two mechanisms, persistent transport network connectivity and cultural convergence, absorb 70% of the ancient connectivity effect. In the absence of adequate data on alternative aspects of convergence such as genetic similarity, we only speculate about other (potentially non-exclusive) mechanisms that explain the residual relationship between effective distance and cross-regional firm ownership.

Our paper contributes to various literatures in trade, economic geography, and long-run development. Directly linked to our research is a literature concerned with identifying determinants of bilateral trade and especially the branch that assesses transport-cost related effects on trade flows (see, e.g., Duranton, Morrow and Turner, 2014; Pascali, 2017; Donaldson, 2018; Feyrer, forthcoming).[6] Our contribution is to compile a spatially highly disaggregated dataset on Roman trade flows and to provide the first empirical evidence that the trade-deterring effect of transport costs, approximated by effective distance, existed during ancient (Roman) times. The fact that distance is relevant implies that—already in antiquity—trade occurred due to specialisation in products or product varieties across regions. To the best of our knowledge, only the recent study of Barjamovic et al. (forthcoming) applies a gravity-type framework to an earlier period (Bronze Age). In contrast to our work, however, trade flows are not observed and trade cost elasticities cannot be estimated.

---

[6] Similarly, Redding, Sturm and Wolf (2011) show that distance between airports reduces bilateral passenger transport.

An expanding literature investigates the effects of transport network accessibility on local economic activity (for an overview, see Redding and Turner, 2015). Many studies focus on analysing contemporaneous effects (see, e.g., Michaels, 2008; Duranton and Turner, 2012; Banerjee, Duflo and Qian, 2012; Faber, 2014; Hornung, 2015; Donaldson and Hornbeck, 2016; Storeygard, 2016; Baum-Snow et al., 2017).[7] A smaller body of work shows that historical transport infrastructure investments influence today's spatial distribution of population and economic activity, even long after the transport networks have ceased to be operational (see, e.g., Jedwab, Kerby and Moradi, 2017; Jedwab and Moradi, 2016; Flueckiger and Ludwig, 2019). Particularly related to our paper are studies that specifically focus on the effects of Roman transport infrastructure. The recent paper by Dalgaard et al. (2018), for example, documents that Roman road network density pre-determines modern road density and thereby influences the level of economic activity today. Using a similar estimation approach, Garcia-López, Holl and Viladecans-Marsal (2015) and Percoco (2015) show that highways affect suburbanization in Spain and location of firms in Italy. In both cases, current highway access is instrumented with the presence of Roman roads. In a recent paper, Wahl (2017) shows that integration into the Roman Empire positively influences current-day economic activity. Again, persistence in access to the road network is identified as the main mediating factor.[8] Similarly, De Benedictis, Licio and Pinna (2018) show that the density of the Roman road system still predicts transport costs across Italian provinces today. We complement these findings by considering all modes of transport in the Roman network—including waterborne transport—and documenting that, in addition to levels of development, historical connectivity influences the intensity of bilateral economic exchange. Although trade is very sensitive to shocks, as recently shown by Eaton et al. (2016), we show that the *relative* intensity in economic integration between regions is highly stable in the long run.

Our study further informs an ongoing debate among historians of the antiquity over whether Rome was a market economy. While there is broad consensus that staples, luxury goods, and a wide range of manufactured products were traded over long distances throughout the Roman period (see, e.g., Hopkins, 1980; Horden and Purcell, 2000; Wilson and Bowman, 2018), the extent to which trade patterns were driven by market forces and trade costs remains disputed. Much of the archaeological literature argues that the frequency and distribution of excavated terra sigillata implies a key role of the state and the military in its production and distribution, i.e., suggesting centralised planning (see, e.g., Whittaker, 1994; Willis, 2005; Fulford, 2018). The notion of government controlled trade is, however, questioned by Wilson and Bowman (2018) and rejected by Polak (2000), Mees (2011), and Mees (2018) who argue that the supply and demand of terra sigillata was not centrally coordinated by the military, but reflects private market forces, i.e., individual soldiers spending their pay. We contribute to this discussion by providing first econometric evidence that the intensity of Roman trade in terra

---

[7] Further related to our paper is the recent study by Bakker et al. (2018) which shows that greater connectedness along the shores of the Mediterranean increased local economic activity (measured by the presence of archaeological sites) during the time of the Phoenicians (Iron Age), when the first systematic crossings of open seas were undertaken. Employing a cross-sectional regression setup, they find that this locational advantage persists through the classical period.

[8] Related to these studies, Gomtsyan (2017) finds a positive relationship between the presence of a Roman road or fort with the share of migrants in today's European cities.

sigillata was indeed determined by transportation costs, implying that market forces mattered.[9] By conditioning on origin and destination fixed effects, our approach allows us to circumvent concerns related to preservation and excavation biases raised in the archaeological literature (Wilson, 2009).

Our findings directly speak to the literature on the determinants of interregional investment. Portes and Rey (2005) show that, similar to trade in physical goods, (geographical) distance also deters exchange in financial assets. In line with this finding, Giroud (2013) and Campante and Yanagizawa-Drott (2018) show that air-link connectivity influences firms' decisions of where to invest. Typically, the literature proposes search and coordination costs arising from information asymmetries and reduced familiarity as mechanisms underlying the distance effect and the home bias in investment decisions (e.g, Head and Ries (2008)). Supporting the importance of these channels, Leblang (2010) and Burchardi, Chaney and Hassan (forthcoming) show that social ties created by historical migration are important determinants of foreign direct investment. Similarly, Guiso, Sapienza and Zingales (2009) find that genetic and somatic similarity affect bilateral trust, which, in turn, influences investment flows between countries.[10],[11] Our results suggest that infrastructure investments of the distant past lead to continued (socio-) economic interaction, fostering convergence in preferences and values, which, in line with the arguments raised in the literature above, affect the spatial pattern of firm ownership today.[12] In this regard, our paper is also related to a literature concerned with explaining differences in economic preferences across space (Tabellini, 2008; Chen, 2013; Galor and Özak, 2016; Litina, 2016; Falk et al., 2018).

Also linked to our paper is the literature on the network structure of trade. The idea that networks influence international trade in differentiated products was first highlighted by Rauch (1999). Empirical evidence for the importance of networks is provided by Rauch and Trindade (2002) based on the analysis of ethnic Chinese networks, by Combes, Lafourcade and Mayer (2005) who investigate trade between French regions, and by Garmendia et al. (2012) on the basis of regional Spanish trade data. Chaney (2014) builds and estimates a structural model in which potential exporters meet their buyers either via direct search or via their established network, highlighting the role of trade costs due to geography as well as costs resulting from information frictions. In the spirit of these models, we focus on a highly disaggregated subnational trade network that was established when the Roman transport network was created and show that it strongly and continuously influences interregional interaction.

Finally, we also connect to the discussion about the determinants of business cycle comovement (see, e.g., Burstein, Kurz and Tesar, 2008; Cravino and Levchenko, 2017). Our results

---

[9] To our knowledge, Kessler and Temin (2008) is the only study that provides econometric evidence for trade costs influencing economic integration during the Roman era. They show that Roman grain price differentials decline in distance (based on six price pairs).

[10] Ahern, Daminelli and Fracassi (2015) document a negative relationship between cultural distance and the volume of cross-border mergers.

[11] Similarly, the trade literature identifies culture and language as some of the most important drivers of bilateral trade flows (see, e.g., Melitz, 2008; Felbermayr and Toubal, 2010; Egger and Lassmann, 2012; Melitz and Toubal, 2014).

[12] A similar convergence of preferences for redistribution is documented by Alesina and Fuchs-Schündeln (2007) who exploit the natural experiment of German separation and re-unification.

highlight that events of the distant past can influence interregional transmission of economic shocks. In our case, the intensity of transmission is determined by connectivity within the Roman transport network.

The remainder of the paper is structured as follows: In Section 2, we provide background information on the creation of the Roman transport network along with narrative evidence of its effect on contemporary trade; characteristics of the traded Roman terra sigillata are also described. The data is presented in Section 3. Section 4 describes our empirical framework; regression results are discussed in Section 5. We investigate potential channels underlying our main results in Section 6, before concluding with Section 7.

2 Background

This section serves two purposes. First, it briefly describes the evolution of the Roman transport network and outlines how it created a new pattern of cross-regional economic integration within the empire. Second, it illustrates why terra sigillata excavated at archaeological sites is well-suited to measure the intensity of interregional trade during the Roman era.

2.1 The Roman transport network and its effect on economic integration

At the time of maximum territorial expansion around 117 CE, the multi-modal Roman transport network consisted of approximately 80,000 km of paved roads, 25,000 km of inland waterways and a vast number of well-established shipping routes along the Mediterranean and Atlantic coasts (Chevallier, 1972; Scheidel, 2014). Starting with the linking of Rome to other regions on the Italian Peninsula, the (spatio-temporal) growth of the network had closely followed the territorial expansion of the Roman Empire. Once occupied, soldiers built roads connecting and cutting through the newly annexed regions in order to facilitate supply shipments and bringing in reinforcements. To minimise building cost and travel times for troops, Roman engineers designed roads to follow straight lines over long distances, thereby often ignoring local geographic and demographic conditions (Davies, 1998; Laurence, 2002).[13] Progress in civil engineering, such as the newly developed ability to construct permanent bridges, helped with the straight-line routing of roads. While the construction and design of roads was determined by military-strategic aims, they were subsequently used for commercial as well as private transport and communication (see, e.g., Temin, 2012, p. 223).

Roadworks followed clear and technologically novel standards, with surfaces consisting of several layers of sand, gravel, and rocks as well as drainage systems (Berechman, 2003). Combined with the construction of new road segments in core and peripheral regions, these technological advances greatly increased the freight-carrying capacity of the road network (Adams,

---

[13] Illustrating that straightness of routing was prioritised over ease of travel is the fact that many road sections did not meander and had steep gradients (Davies, 1998). The military-strategy and straight-line-preference-influenced routing of roads further suggests that roads were not systematically built to connect existing settlements (see, e.g., Laurence, 2002). This assuages concerns related to the possibility of endogenous placement of roads which will be discussed in more detail below.

2012). The embedding of the road system into a unified legal framework constituted a further important Roman innovation that facilitated overland transport. By categorising roads into four groups (*via publica, via militaris, via vicinalis, via privata*), functions, rights of utilisation, and entities responsible for maintenance were clearly defined (Rathmann, 2003).[14] Among other things, this ensured that roads remained in good repair (Berechman, 2003).

Similar to terrestrial transport, capacities and organisation of waterborne transport substantially changed during Roman reign (see, e.g., Schmidts, 2011).[15] Along with the size of boats and ships, the quantity of goods shipped via waterways increased dramatically. Large flat-bottomed barges used for river transport were able to carry around 150 tonnes of cargo. Seagoing ships were even loaded with up to 1,000 tonnes of freight (Campbell, 2012, p. 217). Canals—typically constructed to bypass dangerous parts of rivers or to facilitate navigation through river deltas—also contributed to the reduction of water transportation costs (McWhirr, 2002). Adding to the innovations in terrestrial and waterborne transport infrastructure, the empire-wide (political) stability and peace (pax Romana) further stimulated the establishment and deepening of long distance trade relationships (Sidebotham, 1986, p. 181). Piracy in the Mediterranean, for example, a previously common and trade-deterrent problem, was largely suppressed after 67 BCE (de Souza, 2002, p. 96). The introduction of a common currency as well as improvements in shipping and container technologies (amphorae and barrels) further facilitated long distance trade (see Wilson and Bowman, 2018, p. 5–6).

Information on cross-regional economic interaction before Roman occupation is scarce.[16] While certainly existing, trade among tribes or between Roman merchants and tribes was comparatively limited and localised prior to occupation. Indeed, the amount of Roman goods that pre-date the occupation excavated in Celtic regions (such as amphorae and other pottery products) is considerably lower (Fitzpatrick, 1985, p. 310). Following annexation and integration into the empire-wide transport network, diversity and quantity of exchanged goods substantially changed in core as well as peripheral regions. Once occupied and connected to the transport network, the considerable agricultural surpluses of the former Celtic and Egyptian regions crucially contributed to the food security of Rome and its capital (Erdkamp, 2013). Similarly, new types of cereals, such as emmer and spelt that were unsuitable for cultivation in the north, were imported from southern provinces (Reddé, 2018, p. 147). Access to the transport network also promoted specialisation and the exchange of manufactured products. Various commodities—e.g. amphorae, ceramics, glass, lamps, bronze statuettes—were produced in large quantities at centralized production sites and traded over long distances (Bowman and Wilson, 2009, p. 17). Accompanying economic interaction, the transport network increased interpersonal interaction and thereby induced migration as well as technological and cultural diffusion across regions

---

[14] *Viae publicae*, for example, were constructed and maintained by the state. Maximum load allowances for carts reduced the wear and tear of the pavement (Berechman, 2003). Roads were required to support the heaviest category, i.e. carts up to a weight of 1,500 Roman pounds (around 500 kg) drawn by two pairs of oxen.

[15] An example of institutional change is that river transport was to a large extent controlled by well-organised cooperations of *nautae* (boatmen) (Schmidts, 2011).

[16] For Celtic Gauls there is evidence of considerable trading activity. Ships, for example, were used for river transport. Furthermore, they maintained ports in Britain to control trade with this region. Shipwrecks discovered in the Mediterranean additionally hint at a Celtic ship-building tradition (Schmidts, 2011, p. 93).

(see, e.g., Willis, 2005). Evidence indicates, for example, that the custom of sharing meals was spread by Roman soldiers (Willis, 2005, ch. 7.2.2). As a result of economic and cultural exchange, similar goods and technologies could be found across all Roman provinces (see Wilson and Bowman, 2018, p. 5).[17] The 'Roman consumption package' consisting of amphorae for wine, olive oil, fish products, and table pottery was available throughout the empire (Bowman and Wilson, 2009, p. 17).

In summary, the Roman Empire-wide integrated transport network led to an unparalleled degree of market integration and created a new pattern of interregional (socio)-economic exchange (Bowman and Wilson, 2009, p. 17). While pre-existing roads and waterways may have facilitated initial Roman occupation, the 'barbarian regions' had not been part of an *integrated* supra-regional transport network.[18] Furthermore, technology, routing, density, and maintenance of transport infrastructure substantially changed after Roman annexation. These alterations, along with the unprecedented geographic reach of the network imply that the (bilateral) accessibility between regions dramatically changed.[19] For the first time in history, for example, paved mountain passes permitted the transalpine exchange of large quantities of goods, thereby intensifying economic ties between regions on either side of the Alps (Hitchner, 2012). The fact that new villages and towns formed around stopping points (*mansiones and mutationes*) alongside main roads provides further evidence for the Roman transport network substantially altering the geography of economic integration (Hitchner, 2012, p. 225). By contrast, many Celtic settlements—*oppida*—not well linked to the Roman transport network were either moved to better connected areas (e.g., riverside or roads) or abandoned altogether.[20]

Variation in (relative) costs of shipping goods between regions plays a potentially dominant role in explaining how the Roman transport network shaped the pattern of bilateral exchange. Although disputed among the early historians of the antiquity (see, e.g., Finley, 1999; Jones, 1964; Yeo, 1946), it is plausible that the intensity of trade between regions depended on the costs of transportation. These were determined by the available means of transport and their associated per unit freight rates. For the given Roman transport technology, freight rates varied dramatically across modes. On the basis of emperor Diocletian's *Edict on Maximum Prices* from 301 CE—an original contemporary source—Scheidel (2014) recently revised existing estimates of relative per-unit-distance transport costs.[21] The results illustrate that seaborne transport was the most cost effective mode of shipping with a (normalised) per unit distance freight rate of

---

[17] Hitchner (2003, p. 398) emphasises that "A citizen of the empire travelling from Britain to the Euphrates in the mid-second century CE would have found in virtually every town along the journey foods, goods, landscapes, buildings, institutions, laws, entertainment, and sacred elements not dissimilar to those in his own community."

[18] Until the defeat of Vercingetorix by Caesar in 46 BCE, for example, Romans used local Gaulish roads and seized Gaulish ships to move troops (Chevallier, 1972, p. 25). However, since Gaulish tribes were not unified, no coherent concept of road building, let alone an integrated cross-regional transport network designed for purposes of trade or military campaigns, existed.

[19] We provide empirical support for this notion in Appendix C.2.

[20] Oppida were often established in easy-to-defend locations such as hilltops. When deciding on routing of the network, Roman engineers typically avoided such obstacles. As a consequence, many of these hilltop settlements were abandoned for new market places and settlements nearby new roads and rivers. For literature on the abandoned *oppida* settlements of Colchester Sheepen, Nijmegen Oppidum Batavorum, Mont Beuvray Bibracte, and Budapest Gellért Hegy, see Niblett (1985); van Enckevort and Thijssen (2009); Labaune and Meylan (2011); Borbála (2006).

[21] See Appendix A.3 for more details on the price edict and the derivation of freight rates.

one, followed by downstream and upstream river transport with associated costs of 5 and 10, respectively. Road transport was by far the most expensive way of moving goods. The historical freight rate data suggest a cost of 52, relative to seaborne transport.[22] Some qualitative accounts and case studies indicate that these transport-mode-dependent cost differentials influenced the decision along which routes to ship goods. The geographical distribution of archaeological pottery finds produced at Banassac in the south of France, for example, implies that indirect routes were chosen over distance-wise shortest paths in order to make use of cost-effective means of transport, i.e., sea or river (Mees, 2011, p. 260).

To date, there is no systematic assessment of the effects of transport costs on interregional trade during the Roman era. The first principal aim of this paper is to fill this research gap. To this end, we require historical data on bilateral transport costs and trade volumes. The former can be inferred by combining data on relative freight rate differentials across shipping modes with information on the structure of the Roman transport network. As outlined below, measures of the magnitude of interregional trade flows can be constructed based on the spatial distribution of terra sigillata excavations.

The second aim of this paper is to analyse how differences in connectivity within the Roman transport network influence economic integration today. In this context, it is important to note that today's routing of roads is strongly influenced by the paths chosen by the Roman engineers.[23] Furthermore, relative transport costs across shipping modes were relatively stable until the advent of the transport in the 19th century.[24] However, with the introduction of new transport technologies, such as steam engines, railways and later on aeroplanes, cost ratios changed substantially.[25] These changes were so profound that they could have had the potential to re-structure the pattern of bilateral interaction.

2.2 Production and trade of terra sigillata

Gallo-Roman terra sigillata is a red-gloss tableware made out of clay which was manufactured at several large production centres in Italy (est. 1st century BCE), Gaul (est. 1–2 century CE),

---

[22] While there is some debate about the appropriate estimates of *absolute* levels of transport costs among historians, there is broader consensus that the above-mentioned cost ratios are reflective of *relative* freight rate differentials during Roman times (see Scheidel, 2014, p. 9). The first price-edict-based estimates produced by Duncan-Jones (1974), for example, suggest the following cost ratios: 1 (sea), 4.9 (river), and 34–42 (road). Additionally taking differences in upstream and downstream river transport into account, more recent studies estimate relative costs of 1 (sea), 5 (downriver), 10 (upriver), 34–42 (road) on the basis of the price edict (Franconi, 2014, p. 57).

[23] There are many examples of today's highways following Roman roads. Well-known stretches include Arles to Aix, Clermont-Ferrand to Limoges, Arcachon to Bordeaux, Saintes to Poitiers. In fact, the surfaces of these roads consisted of the original Roman cobbles and gravel until the introduction of railways in France (Hitchner, 2012). Likewise, British Ordnance Survey Maps document that approximately 3,200 km of modern roads follow Roman road trajectories. Three of the four royal highways of medieval Britain were originally built by the Romans (Watling Street stretching 322 km from London to Chester, Ermine Street stretching 322 km from London to York, and Fosse Way stretching 354 km from Lincoln to Exeter).

[24] Masschaele (1993) calculates relative transport costs in 18th-century England of 1 (sea); 5 (river); 23 (roads). Johnson and Koyama (2017) use calculations by Bairoch (1990) to predict relative costs of 1; 4; 10 for pre-industrial Europe.

[25] For the period shortly after the introduction of steam-powered engines (1861–1930), Donaldson (2018) estimates relative cost ratios of 1 (railway), 2.250 (road), 2.375 (river), 6.188 (coastal) for India.

Germania and Raetia (est. 2–3 century CE). These centres, whose location were determined by clay deposits, produced millions of pieces using an unprecedented division of labour. At La Graufesenque (South France), for example, batches of more than 30,000 vessels were common; kiln firings reached very high temperatures (around 950 degrees Celsius) and were shared by up to twelve potters (Marichal, 1988; Polak, 1998).[26] Potters stamped their names in the inside of vessels to identify their works and distinguish between production batches (Wilson, 2009, p. 397). Based on these stamps, each piece of tableware can be traced from production site to the location of consumption, where it was later excavated by archaeologists. This ability to identify origin and destination of (stamped) products is—in the context of our study—a unique property of terra sigillata.

A second aspect that makes it well-suited for our analysis is its widespread use. Measured as a share of Roman trade, terra sigillata accounted for approximately 10 percent of total volume and an even higher proportion of value (Mees, 2018).[27] High-quality Gallo-Roman terra sigillata—often produced at kiln sites located in hard-to-reach inland regions—was traded across most of the Mediterranean, the Northwestern Empire, the Danube region, and the Barbaricum up to Poland. It even penetrated markets as far as India (Mees, 2018). Low quality ceramic cooking ware and amphorae, in contrast, were almost exclusively manufactured at coastal kiln sites, thus allowing for a cost-effective distribution (see Wilson and Bowman, 2018, p. 10–11). Due to the wide range of terra sigillata products—such as bowls, cups, platters, amphorae, and mortaria—demand stemmed from a great variety of sources, including public, private and commercial entities located in urban as well as rural areas. The distribution of terra sigillata was organised in sophisticated logistics chains. Rather than directly delivered to individual costumers, it was typically shipped in bulk from production sites to warehouses and shops (Willis, 2005, ch. 6.4.6). Terra sigillata produced at La Graufesenque and destined for consumption in the northern border region of the empire, for example, was first transported via mountainous roads to Narbonne (thereby circumventing the Gorges du Tarn canyon). There, it was transferred to barges and shipped upstream on the Rhône to Lyon, the regional trade centre. It was then stored in warehouses until further distribution (Mees, 2011).

The geographical distribution of production and excavation sites of stamped terra sigillata—on the basis of which we construct our measure of bilateral trade intensity—is depicted in Figure 1.[28] There is substantial debate among historians about the (relative importance of) factors explaining the spatial diffusion of terra sigillata. Fulford (2018), for example, observes that there is no clear relationship between the location of pottery finds and (Euclidean) distance to manufacturing sites. Similarly, Weber (2012), remarks that terra sigilliata produced in Gaul was much more common in Britain than products manufactured at Rheinzabern, despite both being located in approximately similar Euclidean distance to London. At many archaeological sites,

---

[26] Figure A.1 depicts (examples of) kiln sites and excavated terra sigillata products.

[27] The price for a piece of terra sigillata typically ranged from 12 to 20 *asses*, equivalent to the daily pay of a soldier (Darling, 1998, p. 169).

[28] Note that the Figure only depicts production and excavation sites that lie within Western Europe, i.e. the geographical scope of our analysis (see Section 3).

excavated potsherds stem from variety of (geographically dispersed) manufacturing sites.[29] Possibly important factors explaining the varying penetration of different terra sigillata products are taste for variety as well as variation in quality and shipping costs. Depending on the available transport modes, the latter could vary greatly, even for two regions located equidistant from a given production site. By employing a gravity-type equation approach, we isolate the effect of transport costs from other factors and estimate to what extent they influenced interregional trade flows and thus help explain the spatial distribution of archaeological finds.

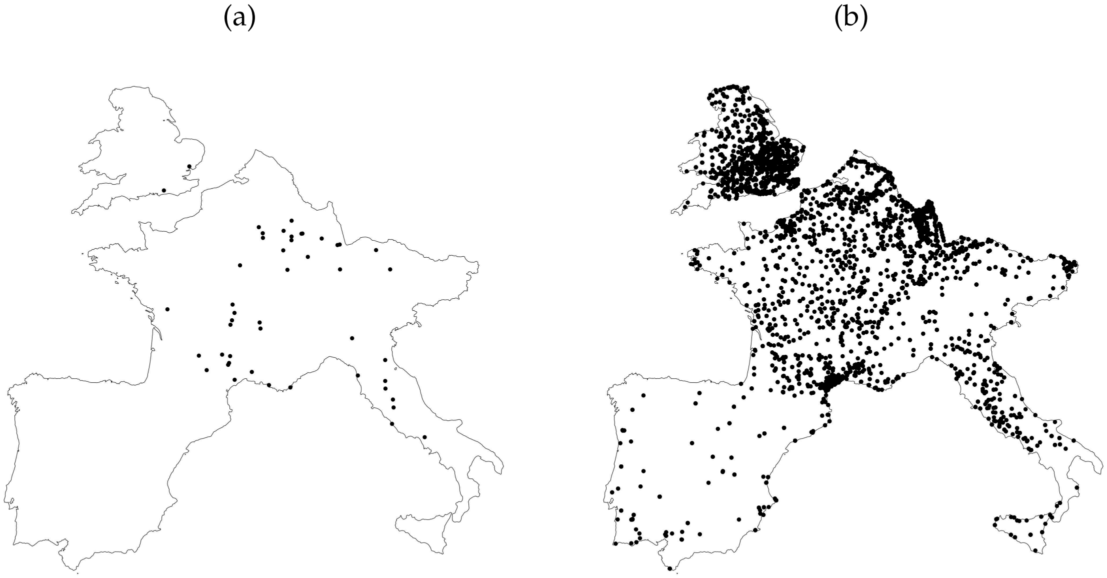

Figure 1: Origins and Destinations of Roman Terra Sigillata
Panel (a) depicts the locations of terra sigillata production sites; panel (b) shows the spatial distribution of terra sigillata excavation sites. Figure is restricted to geographical scope of our analysis.

3 Data

Our study covers the territory of modern-day countries Austria, Belgium, England, France, Germany, Italy, Luxembourg, Netherlands, Portugal, Spain, and Switzerland that once lay within the borders of the Roman Empire. For the empirical analysis, we divide this area—which is referred to as 'Western Europe'—into equally sized grid cells of 0.5×0.5 degrees (approximately 55×55 kilometres). In our analysis, we only consider grid cells that are intersected by the Roman transport network. Illustrating the high density of the network, these grid cells cover 88% of the territory of Western Europe.[30] The aim of this paper is to investigate the effect of the Roman transport network on bilateral economic integration, both in the Roman era and today. To empirically address these questions, we construct grid-cell-pair-level measures of (i) trans-

---

[29] Weber (2012) analyses potsherds excavated at former warehouses and finds 147 vessels stamped by 11 different potters in Wroxeter and 276 vessels from 11 different potters in Castleford.

[30] Figure A.2 depicts the grid cells that are intersected by the Roman transport network.

port network connectivity, (ii) economic integration during Roman times, and (iii) current-day intensity of economic ties.

Transport network connectivity

We predict the cost of transporting goods between two regions during the Roman era under the assumption that agents can use the full, empire-wide, Roman transport network at its maximum extent (corresponding to the year 117 CE).[31],[32] To this end, we combine information on location of Roman roads, navigable rivers and coastal routes. The road network is extracted from the digitised version of the Barrington atlas of the Greek and Roman world (Talbert and Bagnall, 2000).[33] Based on a wide range of historical sources—listed in Table A.1 and including, for example, Campbell (2012) and Dannell and Mees (2015)—we identify navigable river sections that were used for transport by the Romans and are located in regions that are relevant for the construction of least cost paths. Transport by sea is possible along the coast. Combined, roads, navigable rivers, and coastal routes, make up our multi-modal Roman transport network. This network—depicted in Figure 2—is subsequently denoted by $\mathbf{N}^{Rome}$ and represents a collection of numerous segments which differ in length and associated mode of transport.

As outlined above, the cost of shipping goods over a given distance varied substantially across transport modes, whereby relative costs were determined by Roman-era-specific transport technologies. The differences in relative costs are captured by the vector $\boldsymbol{\alpha}^{Rome} \equiv \left(\alpha^{sea}, \alpha^{river}, \alpha^{road}\right)$. Drawing on work by Scheidel (2014), we set $\boldsymbol{\alpha}^{Rome} = (1, 7.5, 52)$.[34] The relative cost of shipping goods via rivers (7.5) represents the average between up- and downstream freight rates (5 and 10, respectively). In our main analysis, we use the undirected rather than the directed transport network to identify the least cost paths.[35] Two reasons motivate this choice. First, when analysing the effects of the Roman transport network on the intensity of interregional business links today, it is not *a priori* clear how transport-direction-dependent cost differentials should affect the direction of parent-subsidiary relationships for a given grid-cell pair. Second, in auxiliary regressions presented in Section 5.1, we employ measures of bilateral interaction that do not allow for a distinction between origin and destination.[36] In these cases, we would have to arbitrarily choose (impose) a directed structure.

Combining information on the network and relative, transport-mode dependent, freight rate differentials (captured by the vector $\boldsymbol{\alpha}$), we can compute the overall cost of transporting

---

[31] This implies that agents can—in order to transport goods between two Western European regions—also choose routes that cross areas that lie outside Western Europe.

[32] Compared to the Stanford geospatial network model of the Roman world (ORBIS) our data source offers a greater geographical coverage in terms of routes and sites. Furthermore, the broad spectrum of information drawn upon when computing bilateral transport costs in the ORBIS project raises concerns that connectivity within the ORBIS transport network is partly determined by observed interaction (i.e., endogenous) during Roman times. Network segments, for example, are ranked according to their significance.

[33] `http://darmc.harvard.edu`.

[34] The freight rates are normalised such that $\alpha^{sea} = 1$. For more details, see Section 2.

[35] This choice is inconsequential for our analysis. As illustrated in Tables C.5 and C.6, results are similar if we use the directed instead of undirected transport network to predict shipping costs. In the directed network, upstream river transport is more expensive (10) than downstream river transport (5).

[36] An example of such a measure is price correlation between two grid cells.

Figure 2: The Multi-Modal Roman Transport Network
Map shows the Roman transport network (restricted to the geographical scope of our analysis). Grey lines symbolise roads, solid black lines navigable river sections, and dashed lines coastal shipping routes.

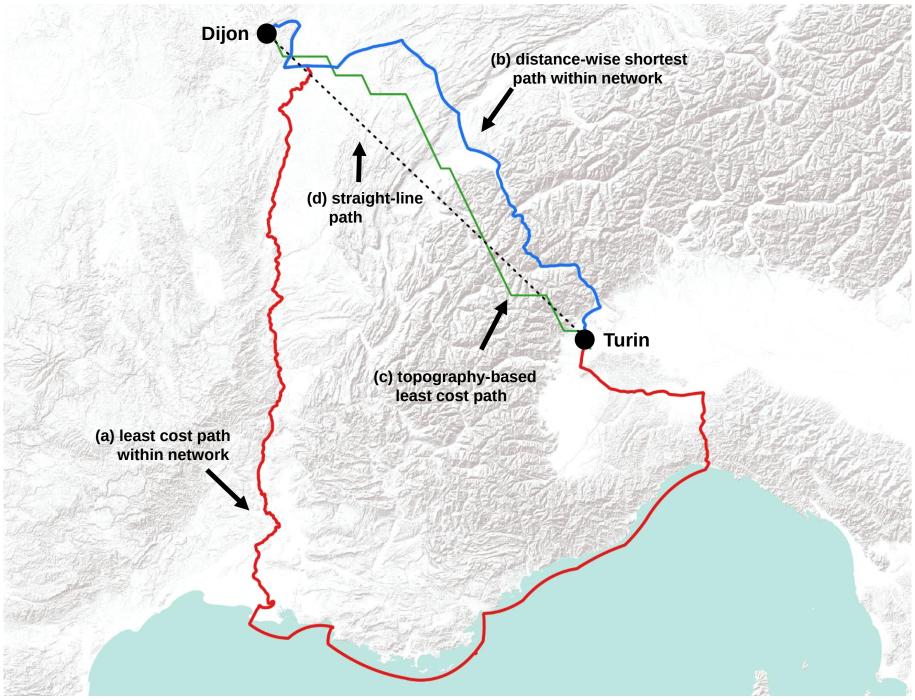

Figure 3: Least-Cost Paths
Map depicts four different least-cost paths between Turin and Dijon: (a) The least-cost path within the Roman transport network, given $\mathbf{N}^{Rome}$ and the Roman-specific technology $\boldsymbol{\alpha}^{Rome}$. The transport cost associated with this path is given by the effective distance ($LC(\mathbf{N}^{Rome}, \boldsymbol{\alpha}^{Rome})$). (b) The distance-wise shortest path within the Roman transport network. (c) The topography-based least-cost path identified using the Human Mobility Index with Seafaring (Özak, 2018). (d) The straight-line (as the crow flies) path. The length of this path is equal to the Euclidean distance.

goods between two locations along any given route as the transport-cost-weighted total length of the individual segments. To predict transport costs between two grid cells, we assume that agents choose the cheapest among all possible routes given the Roman-era-specific, technology-driven, transport cost differentials $\boldsymbol{\alpha}^{Rome}$ and the Roman transport network $\mathbf{N}^{Rome}$. The least-cost path is then identified using Dijkstra (1959)'s algorithm, where the geographical centres (centroids) of grid cells are set as origins and destinations, respectively.[37] Throughout, we assume that transshipment between different transport modes is costless. Following Donaldson (2018), we refer to the costs associated with transporting goods along the optimal path as the 'least-cost path effective distance' or simply 'effective distance'. Subsequently, this cost is denoted by $LC(\mathbf{N}^{Rome}, \boldsymbol{\alpha}^{Rome})$ and we employ the natural logarithm of this measure as our main explanatory variable ($\ln LC(\mathbf{N}^{Rome}, \boldsymbol{\alpha}^{Rome})$).

For illustration, Figure 3 depicts four different least cost paths between Turin and Dijon: (a) The least cost path within the Roman transport network given Roman transport technology (i.e., $\boldsymbol{\alpha}^{Rome}$). As described above, the cost associated with shipping goods along this path is captured by the effective distance (i.e., $LC(\mathbf{N}^{Rome}, \boldsymbol{\alpha}^{Rome})$). (b) The distance-wise shortest path within the Roman transport network.[38] The cost associated with using this path—which we subsequently refer to as network distance—is equal to the length of the path as measured by the number of kilometres. The Network distance can alternatively be interpreted as the most direct route within the Roman road network, since it largely follows roads. (c) The topography-based least-cost path identified on the basis of the Human Mobility Index with Seafaring (HMISea, Özak (2018)).[39] This index takes into account human biological constraints, as well as geographical and technological factors that influence pre-industrial human mobility. The HMISea least-cost path is therefore not dependent on the transport network $\mathbf{N}^{Rome}$. The costs associated with this optimal path is captured by travel time (in minutes) and referred to as topography-based distance. (d) The straight-line connection (as the crow flies). The length of this line—also interpretable as costs—is equal to the Euclidean distance between Turin and Dijon.

Figure 3 illustrates three important points: First, the cost of shipping goods along any of the three (terrestrial) least-cost paths is correlated with Euclidean distance. This is generally true for any least-cost path. Second, the distance-wise shortest path within the network as well as the topography-based least cost path follow the straight line rather closely. This implies that the cost of transporting along these two optimal paths is highly correlated with Euclidean distance.[40] Third, within the transport network, there is a pronounced difference between the least cost path and distance-wise shortest path. The detours taken by the least cost path are due

---

[37] Grid cell centres are connected to the transport network by creating an artificial straight-line road segment between the centroid and the closest point on the section of the network that intersects the grid cell (similar to Donaldson and Hornbeck, 2016). This procedure is motivated and illustrated in more detail in Appendix C.1. On average, we create an artificial road of 7.5 kilometres, representing 6.9% of the total cost of the optimal path. Our results remain qualitatively unchanged if we choose the point on the network that is closest to the grid cells's centre (without artificially adding the connecting road segments) as origin/destination (see Tables C.1–C.2).

[38] To identify the shortest path, we abstract from any cost differentials across transport modes. That is, we set $\boldsymbol{\alpha} = (1, 1, 1)$.

[39] See Appendix C.6 for more details.

[40] The fact that the distance-wise shortest path within the network closely follows the straight-line (as the crow flies) connection illustrates the high density of the network.

to Roman-era-specific, technology-based, differences in shipping costs across transport modes, i.e., $\boldsymbol{\alpha}^{Rome}$.[41]

The positive relationship between Euclidean distance and effective distance implies that $LC(\mathbf{N}^{Rome}, \boldsymbol{\alpha}^{Rome})$ may be correlated with Roman-era-unspecific connectivity measures, such as transport costs along the topography-based HMISea path. To identify Roman-era-specific variation in $LC(\mathbf{N}^{Rome}, \boldsymbol{\alpha}^{Rome})$, we therefore control for Euclidean distance in our empirical analysis. Conditional on Euclidean distance, the remaining variation in $LC(\mathbf{N}^{Rome}, \boldsymbol{\alpha}^{Rome})$ is determined by the Roman-era-specific technology ($\boldsymbol{\alpha}^{Rome}$), which—ceteris paribus—affects the length of the detour, given the available routes, and the average costs associated with each segment of the detour (i.e., the mode of transportation).

Measuring economic integration during the Roman era: terra sigillata

To measure bilateral trade volumes during Roman times, we extract information on terra sigillata finds from the comprehensive Roman tableware database which has recently been made available online by the Römisch-Germanisches Zentralmuseum in Mainz.[42],[43] As discussed in Section 2, we can identify the origin of terra sigillata based on the potter's stamp and its destination based on the site of excavation. The stamped vessels were produced between the beginning of the first century and the middle of the third century. During the period 75–125 CE, a range of terra sigillata products were not stamped. These unstamped items amount to approximately 30% of total excavated terra sigillata (Furger and Deschler-Erb, 1992, Fig. 84).[44] Crucial for our analysis, there is no indication that shipment and distribution of these types systematically differed from stamped types.

Based on precise information of both, site of production and excavation (see Section 2), we assign each find to its grid cell of origin and destination. We then aggregate this information to the grid-cell-pair level. The result—the number of terra sigillata finds within grid j that were produced in grid i—represents our measure of aggregate, interregional trade flows.[45] The 47 individual production sites identified in the database fall into 36 different grid cells. For the Roman era, we thus have 36 origin grid cells from which goods can potentially be shipped to 903 regions. For 560 of these grid cells we observe at least one terra sigillata find manufactured in any one of the 36 'production grid cells'. Abstracting from within grid-cell trade, our dataset for the historical analysis consists of 20,125 observations.[46] The intensity of terra sigillata trade

---

[41] The distance-wise shortest connection between Turin and Dijon exclusively uses roads, whereas transporting goods along the least cost path is associated with the use of all three transport modes: roads, rivers, and sea. As mentioned above, the latter two are much more cost effective.

[42] `https://www1.rgzm.de/samian/home/frames.htm`.

[43] The samian data is based on the publications of Names on Terra Sigillata (see Hartley et al., 2008) and the Corpus Vasorum Arretinorum (see Oxé, Comfort and Kenrick, 2000).

[44] This implies that terra-sigillata-based estimates of variation in trade over time would need to be interpreted with caution and may suffer from measurement error.

[45] For the main analysis, we aggregate trade flows across production sites within grid cells. Our results remain qualitatively unchanged if we aggregate trade flows to the production-site level and run regressions at the production-site-destination-grid-cell level. To that end, we augmented Eq. (1) to include production site and destination fixed effects. The results are presented in Table C.4.

[46] Note that within our regression setup (see Section 4 below) any grid cell with zero terra sigillata finds *and* zero

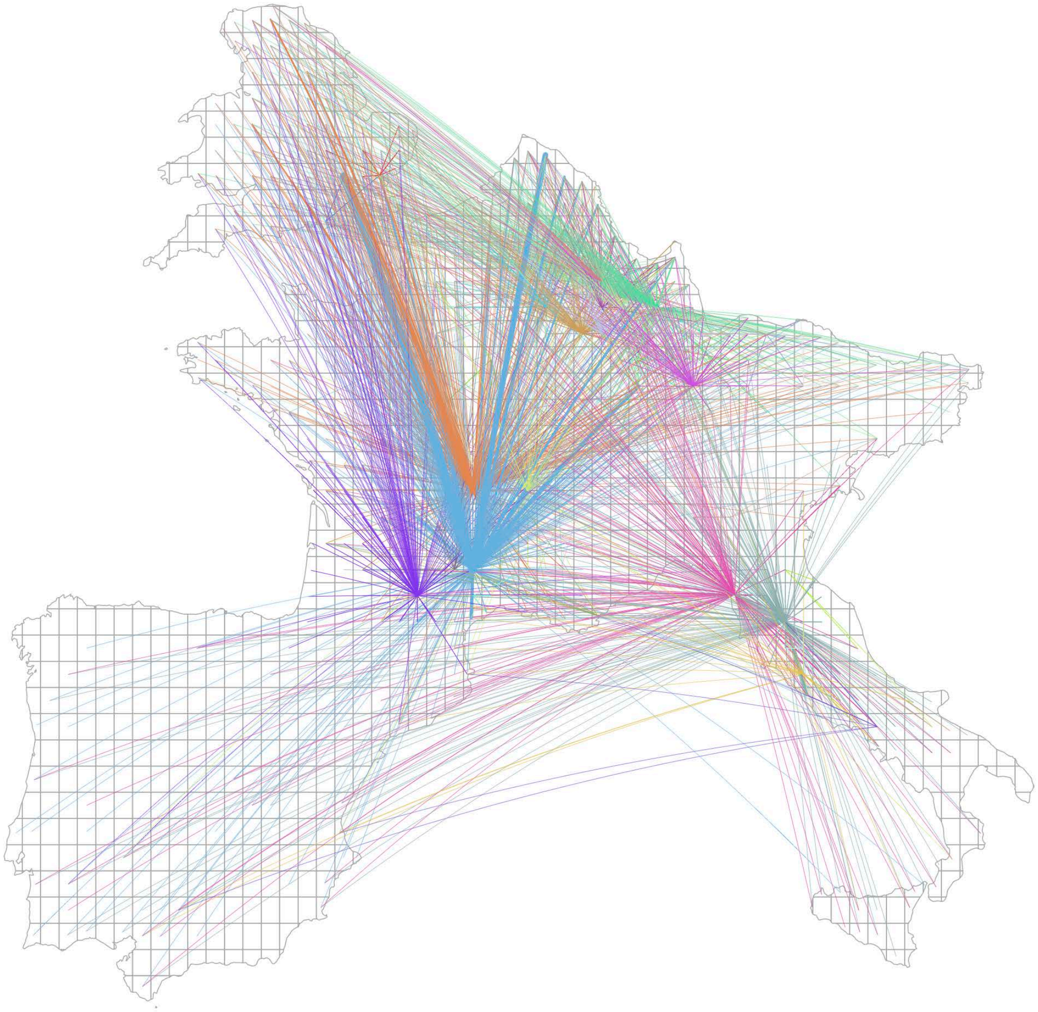

Figure 4: Bilateral Trade Flows in Terra Sigillata during Roman Era
Figure maps trade flows of terra sigillata between grid-cell pairs. Each colour is specific to one origin grid cell. Thicker lines indicate larger volumes of flows.

varies substantially across grid-cell pairs, ranging from zero to 11,768 finds (see Table A.3 where summary statistics of the key variables are reported). The greatest volume of trade is observed between the grid cell that contains production sites Banassac and La Graufesenque and the cell in which London is located.[47] Figure 4 depicts all trade flows.

Measuring economic integration today: cross-regional firm ownership

The number of cross-regional firm ownership links is constructed from the Bureau van Dijk's Orbis database (for similar applications see, e.g., Cravino and Levchenko, 2017; Campante and Yanagizawa-Drott, 2018). This database covers around 300 million companies worldwide and contains detailed firm-level information on industry, location, and ownership. For our analysis, we focus on firms with an annual operating revenue of more than 2 million U.S. dollars. To compute the grid-cell-pair number of business links, we first identify all firms that are located within Western Europe (as defined above). Among these firms we then extract the subset of companies that are in a cross-regional parent-subsidiary relationship. Specifically, we keep all firms that either own a stake of at least 25% in another firm that is domiciled in a different grid cell or that are 25% owned by a company registered in another grid cell.[48] The location of these firms was geocoded manually. For our analysis, we are left with 106,996 cross-regional parent-subsidiary links. These business links are aggregated to the grid-cell-pair level by counting the number of firms located in 'destination grid cell' j that are (part-)owned by firms registered in 'origin grid cell' i. Our final grid-cell-pair-level dataset consists of 731,823 observations, made up of 865 origin and 847 destination grid cells.[49] The number of parent-subsidiary links between grid cells varies between zero and 1,225 (see Appendix A.4). The data was downloaded from February–April of 2018, and consequently captures a snapshot of ownership patterns as of that point in time.

4 Empirical framework

To estimate the effect of the Roman transport network on economic integration—past and present—we employ the following regression setup:

$$\mathcal{X}_{ij} = \delta \ \ln LC(\mathbf{N}^{Rome}, \boldsymbol{\alpha}^{Rome})_{ij} + T'_{ij}\,\gamma + \beta_i + \beta_j + \varepsilon_{ij}. \tag{1}$$

The dependent variable $\mathcal{X}_{ij}$ represents our measures of bilateral (socio-)economic integration between grid cell i and j, such as historical trade volumes or current-day business link intensity. The main explanatory variable is the least-cost path effective distance, $LC(\mathbf{N}^{Rome}, \boldsymbol{\alpha}^{Rome})_{ij}$. As described above, the effective distance between two regions is determined by the structure of

---

production sites is excluded due to collinearity.

[47] Note that the inclusion of origin and destination fixed effects will account for differences in the overall level of trade volumes (e.g., for the fact that London, as major city, imports a lot of terra sigillata). See Section 4 for more details.

[48] As shown in Table C.11, our results are not sensitive to increasing the threshold to 50%.

[49] In analogy to the historical analysis, any grid cells with zero parents *and* zero subsidiaries are omitted (see Section 4).

the transport network $\left(\mathbf{N}^{Rome}\right)$ and the mode-specific differences in transport costs $\left(\boldsymbol{\alpha}^{Rome}\right)$. T_{ij} is a varying set of variables encompassing factors that potentially influence economic integration (e.g., Euclidean distance or topography-related barriers). When this set is empty, i.e., when we estimate Eq.(1) without controlling for further measures of resistance, the coefficient δ captures the elasticity of economic integration with respect to the effective distance.[50] Whenever T_{ij} includes our full set of controls, δ captures the part of the transport network effect that is Roman-era specific.

Throughout our analysis, we control for the full set of origin and destination fixed effects (represented by β_i and β_j, respectively). Crucially, these dummies control for market size which, in addition to trade costs, is a central feature of a gravity-type equation and capable of explaining bilateral trade flows.[51] More generally, the fixed effects dummies absorb any differences in region-specific characteristics—such as population size, income levels or geographical location—that influence the overall level of economic integration. In the context of archaeological data, it is further important to note that the fixed effects wash out potentially existing excavation biases, i.e., the possibility that discovering Roman tableware is more likely in economically more integrated and populated areas. Finally, the inclusion of origin-specific dummies also controls for production-site-specific quality differences that influence the magnitude of interregional trade flows.[52]

Even though the fixed effects account for several potential sources of confounders, there remain a number of threats to identification. Of particular concern is endogenous routing of the road network. That is, the possibility that roads were specifically built to more directly connect region pairs that already interacted relatively intensely.[53] As outlined in Section 2, historical evidence suggests that this was not the case. In Sections 5.1 and 5.2 we provide more formal evidence corroborating the historical narrative and discuss further potential threats to our identification strategy.

Following Santos Silva and Tenreyro (2006), we estimate our equation (1) taking the exponential of the right-hand side and using a Poisson pseudo-maximum-likelihood estimator (PPML) in order to avoid inconsistent estimates due to heteroscedasticity and to take into ac-

---

[50] For the Roman era, δ can directly be interpreted as trade elasticity with respect to transport costs.

[51] Using fixed effects to control for market size was first suggested Anderson and van Wincoop (2003) and prominently promoted by Feenstra (2004, 2016). By including fixed effects rather than explicitly controlling for size, endogeneity issues related to reversed causality are circumvented. The fact that trade openness increases income is well established (see Frankel and Romer, 1999; Wacziarg and Welch, 2008; Feyrer, 2009; Estevadeordal and Taylor, 2013; Feyrer, forthcoming, for prominent examples).

[52] Many trade theories do not allow for quality differences while the prominent heterogeneous firm literature spurred by Melitz (2003) leads to isomorphic results when productivity differences are interpreted as quality differences. Baldwin and Harrigan (2011) discuss the possibility of identifying valid trade theories (including theories that do account for quality differences) by looking at quantities, values, and prices. Lacking information on the latter two dimensions, we cannot identify which theory most accurately explains trade flows during Roman times. However, as we are interested in investigating the effect of trade costs on the bilateral allocation rather than assessing the validity of specific theories, controlling for quality differences using origin and destination fixed effects is sufficient.

[53] Note that endogeneity in local placement of roads does not constitute a threat to identification in the context of our analysis. The fact that a grid cell is cross-cut by (multiple) roads is absorbed by the origin and destination fixed effects. Furthermore, we only include grid cells that are intersected by at least one segment of the Roman transport network. In the context of our study, issues arise only if bilateral (i.e. grid-cell-pair-specific) aspects systematically influenced the routing of the network.

count the information contained in zero trade flows.[54],[55] The error terms, represented by ε_{ij}, are clustered along two dimensions: the origin and destination grid cell level.

5 Main results

The discussion of our empirical results is structured as follows. In a first step, we document that effective distance in the Roman transport network determined the geography of Roman trade. We then show that the Roman-era-specific differences in transport costs continued to shape trade patterns during the medieval and early-modern period. In a third step, we move to the current day and document that variation in effective distance is reflected in today's spatial firm ownership structure. In the final part of the paper, we investigate the mechanisms generating this pattern.

5.1 Roman transport network connectivity and economic integration in the past

5.1.1 Roman transport network connectivity and economic integration during the Roman era

We start our empirical analysis by estimating the trade elasticity with respect to effective distance during the Roman era. The result, presented in column (1) of Table 1, documents that our least-cost path measure is strongly associated with historical trade patterns. The statistically highly significant point estimate of -2.355 implies that a one percent increase in effective distance reduced the volume of bilateral trade by 2.4%. The magnitude of this coefficient is close to the elasticity of -1.912 reported in Barjamovic et al. (forthcoming). Their estimate is obtained using data on joint attestation of city names during the Bronze Age. Donaldson (2018)'s trade-cost elasticity estimate of around -1.6 for 19th and 20th-century India is somewhat smaller. Compared to estimates of modern-day trade elasticity, our effective distance coefficient is larger in absolute terms. In a survey covering 103 papers, Disdier and Head (2008) find an average distance elasticity of -0.9, with 90% of the coefficients lying between -1.55 and -0.28. Similarly, Head and Mayer (2014) conduct a meta analysis of 2,508 estimates reported in 159 papers and find an average distance elasticity of -0.89 across all gravity estimates and of -1.1 when focusing on structural gravity models alone.[56] Regardless of the controls included, our point estimates for the Roman era are at the upper end or above these intervals. This implies that the importance of distance has declined over time, which is in line with the common perception of decreasing transport costs and increased globalisation.

The fact that a gravity-type relationship holds for Roman trade in terra sigillata implies that we observe regional specialisation in products or product varieties, which, in turn, leads to exchange of products or varieties, i.e., trade between regions. Many prominent theoretical

---

[54] We use the Stata command `ppmlhdfe` developed in Correia, Guimarães and Zylkin (2019) to estimate Eq. (1).

[55] Our measure of trade flows in the Roman era is based on the number of tableware finds. This is a count variable and therefore provides another motivation for estimating a Poisson model. In auxiliary regressions, we also employ non-count variables as regressands. In this case, we estimate Eq. (1) using ordinary least squares.

[56] Note that many surveyed studies proxy trade costs by Euclidean distance, whereas our measure is effective distance.

underpinnings of the gravity model are built on the existence of product varieties which induce intra-industry trade (see Anderson, 1979, for one of the seminal contributions). Such a framework matches well with our terra sigillata data, where product type and quality likely vary across production sites (see Section 2).[57]

Table 1: Roman transport network and trade during Roman era

Dependent Variable:	Number of Terra Sigillata Finds				
	(1)	(2)	(3)	(4)	(5)
ln effective distance	-2.355*** (0.387)	-1.783*** (0.409)	-2.109*** (0.382)	-0.943*** (0.358)	-1.373*** (0.350)
Joint duration under Roman rule (centuries)		2.620*** (0.639)	2.146*** (0.652)	1.416* (0.766)	1.677** (0.686)
ln Eucl. distance				-1.036*** (0.296)	
ln network distance					-0.800*** (0.201)
Geography controls	No	No	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes
Observations	20,125	20,125	20,125	20,125	20,125
Estimator	PPML	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of Terra Sigillata finds in a cell i that originates from cell j. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'network distance' measures the length in kilometres of the distance-wise shortest path between grid cell centroids within the Roman transport network. Geography controls include three dummy variables that take the value one if two grid cells are intersected by the same waterway, are both located on the Mediterranean Sea, and are both part of the same biome, and the absolute difference in latitude between grid cell centroids. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

In column (2), we control for the number of years (measured in centuries) that two grid cells jointly spent under Roman rule. This variable accounts for the fact that total trade volumes potentially increase with shared time in the same economic and political entity. The fact that two regions were only connected through the Roman transport network once both had become part of the empire increases this likelihood further. Confirming expectations, we observe that the total trade volume between two regions increases by 262% with each additional century shared under

---

[57] All theoretical foundations of the gravity model build on the assumption that there are many more goods than factors, which allows for complete specialization in different products or product varieties across countries (see Feenstra, 2016, p. 133). Gravity is consistent with perfect competition (see Eaton and Kortum, 2002) and monopolistic competition (see Anderson, 1979; Bergstrand, 1985) as well as a constant-elasticity of substitution utility function allowing for love-of-variety. However, the assumptions about trade-incentive-generating differences vary: Anderson (1979) and Bergstrand (1985) assume same productivities across countries, but allow for some monopoly power, Eaton and Kortum (2002) assume productivity differences across countries and perfect competition. But also a perfect competition Heckscher-Ohlin model with a continuum of goods may lead to a gravity-type relationship if factor prices differ (see Davis, 1995). In this case, countries specialise in different goods rather than varieties.

Roman reign.[58],[59] Compared to column (1), the effective distance coefficient decreases by around 24%. When additionally accounting for geographical features in column (3), the point estimate remains relatively stable. The set of geography controls encompasses the absolute difference in latitude between grid-cell-pair centroids, a dummy capturing whether grid-cell pairs have access to the same waterway, an indicator for joint access to the Mediterranean Sea, and a binary variable that takes the value one if grid-cell pairs share the same biome (i.e., the same biological community).

One important determinant of trade within the Roman transport network is arguably straight-line distance (see Section 1 and 4). Hence, we follow the tradition in the trade literature and augment our regression setup to include Euclidean distance in column (4). While we find that—consistent with the trade literature—Euclidean distance strongly deters trade, the coefficient on effective distance remains statistically significant and sizeable. This accords with historical narrative which indicates that the least-cost paths (i.e., transport routes) were highly non-linear in geographical distance (see Section 2).[60] It also implies that a substantial part of the variation in effective distance—and therefore bilateral connectivity—is generated by aspects that are specific to the Roman era, i.e., the structure of the transport network and Roman-technology-specific differences in shipping costs between transport modes.

To illustrate that effective distance does not simply follow network distance, i.e. the distance-wise shortest path, we exchange the Euclidean distance control with network distance (measured in kilometres) in column (5).[61] The point estimate of our least-cost path measure remains stable compared to column (4). Interestingly, the coefficient of the shortest route is similar in size compared to the point estimate of Euclidean distance. This result arises due to the fact that the purely distance-based connectivity measure (i.e., network distance) is highly correlated with Euclidean distance (bivariate correlation coefficient of 0.96).[62],[63] The strong correlation illustrates the high density of the Roman network within which moving troops (or transporting goods) along a direct route is possible. On the other hand, the low degree of correlation between effective distance and network distance implies that traders made substantial detours to reach

---

[58] Note that the PPML estimator specifies the conditional mean as $E[\mathcal{X}_{ij}|\mathbf{X}] = \exp(\mathbf{X}\boldsymbol{\beta})$, where $\mathbf{X}$ collects all explanatory variables. Hence, the marginal effect of the exogenous variable x_k is given by $\partial E[\mathcal{X}_{ij}|\mathbf{X}]/\partial x_k = \exp(\mathbf{X}\boldsymbol{\beta})\beta_k$. Reformulating leads to $(\partial E[\mathcal{X}_{ij}|\mathbf{X}]/\exp(\mathbf{X}\boldsymbol{\beta}))/\partial x_k = (\partial E[\mathcal{X}_{ij}|\mathbf{X}]/E[\mathcal{X}_{ij}|\mathbf{X}])/\partial x_k = \beta_k$, which implies that the coefficients can be interpreted as semi-elasticities.

[59] Due to the fact that we do not have detailed information on timing, neither on trade flows nor on the evolution of the Roman transport network, we cannot exploit time variation in our analysis. However, as mentioned previously, our results remain qualitatively unaltered if we run our regressions at the production-site level and include production site fixed effects. These dummies account, to a certain extent, for differences in timing, as production sites were operative at different times.

[60] The bivariate correlation coefficient between Euclidean distance and effective distance is 0.37.

[61] To identify the shortest route, we abstract from any cost differentials across transport modes. That is, we set $\boldsymbol{\alpha} = (1,1,1)$.

[62] We obtain qualitatively equivalent results if we replace the distance-wise shortest route with the time-wise quickest route, where transport-mode dependent per-unit travel times are taken from Scheidel (2014). This strongly suggests that variation in transport costs, and not general accessibility (such as time- or distance-wise bilateral connectivity), shaped trade geography during the Roman era.

[63] If we simultaneously control for Euclidean and network distance, the point estimate of the latter changes sign and becomes positive. This is due to the high degree of correlation. The coefficient of effective distance, on the other hand, remains stable.

and make avail of more cost-effective transport modes.

5.1.2 Addressing endogeneity concerns

Overall, the results presented in Table 1 show that greater connectivity within the Roman transport network increased the intensity of contemporary economic interaction across regions. In order to interpret our estimates causally, we require that—conditional on controls—effective distance is uncorrelated with exogenous factors in the error term that influence bilateral trade flows. An immediate concern is that connectivity within the Roman transport network simply reflects pre-existing patterns of bilateral exchange. It is conceivable, for example, that roads were constructed to more cost-effectively connect two already closely interacting regions. However, as discussed in Section 2, historical evidence indicates that the construction and routing of roads was primarily driven by strategic military aims. Furthermore, technological progress and changes in institutional settings led to a substantial shift in transport costs across modes. This implies that even if the Roman transport network did follow pre-existing paths, the shift in relative transport costs would have changed relative bilateral connectivity.

To provide empirical support for this claim, we investigate whether the least-cost path effective distance influences the probability of observing integration between grid cell i and j in pre-Roman times. Absent direct measures of economic integration (such as trade flows), we construct various proxies for cultural integration based on the spatial distribution of different burial traditions during the Neolithic and Bronze Age. Archaeologists generally agree that the spatio-temporal diffusion of these traditions took place by way of cultural exchange, including migration (Cummings, Midgley and Scarre, 2015, p. 825 ff., Paulsson, 2019, Holst, 2013, p. 117, Childe, 1958, p. 123 ff., Childe, 1930, p.173 ff.).[64] The concurrent existence of different types of burial sites in two regions therefore implies economic and social interaction. As proxy for interaction during the Neolithic, we use the common presence of megalithic structures (megalithic graves such as dolmens and passage graves), the dominant standardised burial tradition of this time (Cummings, Midgley and Scarre, 2015). Interregional interaction during the Bronze Age is measured by the common occurrence of the most widespread burial trend, the Tumulus tradition (e.g., round barrows) which emerged rather suddenly in large parts across Europe and is associated with elite formation (Holst, 2013, p. 103, Darvill, 2013, p. 144). In addition to these indicators of common burial practices, we employ the (concurrent) presence of Celtic settlements (Oppida) in grid-cell pairs during the La Tène culture in Gaul as a proxy for (socio-)economic interaction. This is motivated by the fact that the Celtic culture spread across Europe via migration in the Iron Age.

Table C.3 shows that Euclidean distance reduces the likelihood of interaction and cultural exchange in the pre-Roman era, as measured by all four proxies described above. On the other hand, effective distance—i.e., the Roman transport-technology-specific cost of shipping goods along the not yet existing Roman transport network—has no predictive power for any of the proxies. The effective distance coefficients are statistically insignificant and close to zero. Combined with qualitative evidence from the historical literature, these results strongly suggest that

---

[64] See Holst (2013) for a balanced discussion.

(conditional on controls) variation in our least-cost path measure specifically captures differences in bilateral connectivity that emerged due to the creation of the Roman transport network.

To provide further evidence for the Roman specificity of our results, we show that estimates are unaffected when we control for geography-based least-cost path measures (see Table C.9). These measures, described in Appendix C.6, are designed to capture general, Roman-infrastructure-unrelated, costs of transporting goods and people between regions during the pre-industrial era. The fact that the effective distance coefficient hardly changes implies that connectivity within the Roman network is not primarily determined by geographic features, but by the combination of military-strategic road routing decisions and era-specific, technology-dependent differences in transport costs.

In Table C.7, we run further robustness tests to document the stability of our results. Specifically, we account for additional dissimilarities in geographical and climatic aspects that potentially correlate with effective distance and trade volumes. The set of additional controls consists of the absolute difference in longitude, elevation, ruggedness, agricultural suitability, precipitation, and temperature. Furthermore, we employ an alternative clustering approach, where we two-way cluster standard errors at 1×1 degree 'super-grid-cell' level. We additionally show that effective distance reduces trade along the intensive as well as the extensive margin. In Tables C.1 and C.5 we document that our results remain stable if we connect the grid-cell centroids to the network without adding artificial road segments or use the directed network (in which we differentiate between up- and downstream river transportation) to calculate effective distance.

In sum, the results presented so far show that the creation of the Roman trade network strongly influenced the contemporary geography of trade. Our ultimate aim is to analyse whether the transport-network-induced connectivity influences the pattern of cross-regional business links today. That is, we want to relate events that are separated by two millennia. This immediately raises concerns that any detectable relationship between effective distance and current-day outcomes is not the result of continued, Roman-network-induced, interaction, but the product of entirely unrelated processes. To mitigate this concern, we show that differences in effective distance continuously influenced the intensity of interregional economic integration during the medieval and early-modern period until the beginning of the Industrial Revolution.

5.1.3 *Roman transport network connectivity and integration during the Medieval and early-modern era*

Absent spatially disaggregated and temporally consistent information on trade flows for the post-Roman period, we construct two alternative measures of market integration. First, we draw on city-commodity-year-level information from the Allen-Unger Global Commodity Prices Database and compute the grid-cell-pair-level commodity price correlation over the period 1321–1790.[65] This corresponds to the time span between the first year when price data are available and the start of the transportation revolution (i.e., the invention of the steam engine and the railway). In column (1), we focus on cross-regional variation in wheat prices, i.e., a homogeneous

---

[65] Appendix B describes the data and construction process in detail. As price correlation is an undirected measure of market integration, we only include unique grid-cell pairs in our analysis.

and widely traded commodity for which information is consistently available for the whole period. Using this metric, we find market integration between regions that are less well connected within the Roman transport network to be lower. The coefficient of -0.086 implies that price correlation decreases by around 9 percentage points when effective distance increases by one percent. Interestingly, the effect of Euclidean distance is somewhat smaller. This provides additional support for our least-cost path measure to successfully capture variation in trade costs in the pre-industrial era. We obtain similar results, albeit estimated with less precision, when including all commodities in the computation of grid-cell-pair-level price correlation (column 2).[66]

Table 2: Roman transport network and economic integration 1321–1790

Dependent Variable:	Price Correlation Coefficient		Lag Onset
	Wheat	All	Plague
	(1)	(2)	(3)
ln effective distance	-0.086** (0.039)	-0.067* (0.038)	1.854*** (0.473)
Joint duration under Roman rule (centuries)	0.041 (0.026)	0.022 (0.028)	-0.623 (0.511)
ln Eucl. distance	-0.035** (0.016)	-0.050*** (0.017)	0.474* (0.241)
Geography controls	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes
Observations	1,518	1,676	20,908
Estimator	OLS	OLS	OLS

Notes: This table reports estimates of Equation (1) using the OLS estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variables in columns (1)–(2) are grid-cell-pair-level correlations of (1) wheat prices and (2) all commodities reported in the Allen-Unger Global Commodity Prices Database. Dependent variable in column (3) is the time lag in onset of the Black Death. Dependent variables are described in detail in Appendix B. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Second, we use the time lag in onset of the Black Death (1346–51) across grid-cell pairs as a measure of economic integration during the Middle Ages.[67] The use of this metric is motivated by the fact that the Plague spread along trade routes with merchants being the primary carriers of the disease (see, e.g., Cipolla, 1974; Biraben, 1975; Benedictow, 2006). The time lag—constructed using information from 282 cities provided by Christakos et al. (2005) and measured as the absolute difference in the number of months between onset—can therefore be seen as measure of

---

[66] A potential explanation for the loss of power is the introduction of noise when looking at all commodities. For a substantial number of goods, price information is only available for relatively few markets and years.

[67] See Appendix B for details on the construction of the measure.

trade intensity during the Middle Ages (Boerner and Severgnini, 2014).[68] In column (3), we test whether the Roman transport network influenced the spread of the epidemic. The statistically significant and sizeable point estimate implies that increased effective distance substantially widened the time lag in the onset of the Black Death between two grid cells.

Taken together, the results presented in Table 2 empirically substantiate qualitative evidence from the historical literature that indicates that the Roman transport network continued to influence the intensity of bilateral trade at least until to the Industrial Revolution. Qualitative evidence, for example, documents that the Roman road network was continuously used and maintained during the Middle Ages (De Luca, 2016). Arguably, the sustained, Roman-transport-connectivity induced economic exchange also created and intensified social and cultural ties. As these aspects are important determinants of interregional firm investment (see, e.g., Guiso, Sapienza and Zingales, 2009; Leblang, 2010), we expect variation in connectivity within the Roman network to be reflected in today's spatial pattern of business links, even after the introduction of new means of transport and dramatic changes in relative shipping costs across transport modes.

5.2 Roman transport network connectivity and economic integration today

To investigate whether the intensity of interregional business links is influenced by differences in connectivity that emerged due to the creation of the Roman trade network, we continue to use the regression equation (1), but now employ the number of cross-regional firm ownership links as outcome. The shift in focus from analysing the Roman network's effect on trade in goods during antiquity to investigating its influence on the spatial ownership structure today is motivated by a number of factors (see also Section 1). First, cross-country trade is to a large extent processed within multinational firms (see, e.g., Bernard et al., 2010), implying an inherently close relationship between the intensity of bilateral trade and business links. Second, establishing interregional business links is facilitated by networks as they help overcome potential information frictions. Trade can create such networks and thereby reduce these frictions (see Chaney, 2014; Burchardi, Chaney and Hassan, forthcoming). Third, trade in Roman terra sigillata can be regarded as a measure of integration in a more general sense. As outlined in Section 2, variation in the magnitude of trade flows may have determined differences in the intensity of cultural exchange, resulting in reduced information asymmetries and therefore variation in bilateral investment decisions. Finally, while spatially highly disaggregated data on cross-regional business links are readily available, high-quality data on bilateral trade in goods do not exist at a comparable level of (spatial) detail.

In Table 3, we analyse how transport network connectivity during Roman times affects cross-regional business structure today. In column (1), we estimate the relationship between effective distance and the number of firms in region j that are (part-)owned by entities located in region i, conditional on Euclidean distance, a home-country dummy, as well as the complete set of origin and destination fixed effects. When conditioning on Euclidean distance, the effec-

---

[68] Lag in onset of the Plague is, like price correlation, an undirected measure of market integration. We therefore only include unique grid-cell pairs in our analysis.

tive distance coefficient captures only the part of the transport network effect that is Roman-era specific, i.e., generated by variation in Roman-technology-driven differences in transport costs. The point estimate of -0.610 illustrates that this part of the transport cost variation strongly influences today's spatial firm ownership structure. The number of cross-regional firm links decreases by 0.61% with each 1% reduction in connectivity.[69] Column (1) also shows that Euclidean distance exerts a strong negative effect on the intensity of economic interaction and further unveils the existence of a home bias, i.e., cross-regional firm ownership is more common within than across national borders.

Table 3: Roman transport network and interregional firm ownership

Dependent Variable:	Number of Ownership Links (>25% Ownership)				
	Full Sample			Manufacturing	Service
	(1)	(2)	(3)	(4)	(5)
ln effective distance	-0.610***	-0.554***	-0.497***	-0.566***	-0.678***
	(0.102)	(0.109)	(0.119)	(0.101)	(0.171)
ln Eucl. distance	-1.170***	-1.236***	-1.118***	-1.292***	-0.822***
	(0.073)	(0.080)	(0.128)	(0.076)	(0.127)
Intra-national ownership	1.227***	1.113***	1.104***	0.991***	1.570***
	(0.110)	(0.124)	(0.126)	(0.116)	(0.148)
Joint duration under Roman rule (centuries)		0.540***	0.542***	0.597***	0.326
		(0.159)	(0.159)	(0.154)	(0.227)
ln network distance			-0.180		
			(0.144)		
Geography controls	No	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes
Observations	731,823	731,823	731,823	602,597	470,736
Estimator	PPML	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of firms in a cell i that are (part) owned by firms located in grid j. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-national ownership' is a dummy variable that captures whether two grid cells lie within the same country. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'network distance' measures the number of kilometres of the distance-wise shortest path between grid cell centroids within the Roman transport network. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Column (2) documents that the least-cost route coefficient remains stable when we augment the set of controls to include historical and geographical variables. As for Roman trade, the number of years jointly spent under Roman rule strongly increases cross-regional investment intensity. Potential channels underlying this relationship are, amongst others, co-evolution and assimilation of institutions and cultural traits, both friction-reducing factors. In column (3), we additionally control for network distance, i.e., the distance-wise shortest route within the Roman network. The small and statistically non-significant coefficient illustrates that it is not layout of the network as such—i.e., direct, distance-based, connectivity—but the combination of network

---

[69] Not conditioning on Euclidean distance produces an effective distance coefficient of -2.016.

structure and Roman transport-mode-specific differences in transport costs that influence the intensity of economic interaction.

In the last two columns of Table 3, we analyse whether the Roman-transport-network-related effects vary between manufacturing and service parent firms.[70] As the physical transport of goods is (relatively) unimportant for firms within the service industry, this may bring us closer to understanding whether our findings are primarily driven by the continued movement of goods between better connected regions over time. Separately estimating regression Eq. (1) for manufacturing and service ownership companies produces similar, and statistically indistinguishable, point estimates. This result suggests that a range of channels may qualify to explain why the relationship lasts over time. We will elaborate in more detail and investigate the plausibility of various channels in the final section of this paper.

5.2.1 *Robustness and further evidence from the Limes Germanicus*

In order to illustrate the stability of our results, we run robustness tests in analogy to Section 5.1. Table C.8 shows that our estimates remain stable when we include additional geographical and climate controls, employ an alternative standard error clustering approach, or separately look at the intensive and extensive margin of cross-regional ownership intensity. Furthermore, effective distance continues to exert a statistically significantly negative effect if we account for structural differences between countries (such as linguistic distance, average Euclidean distance of differences in national institutions) by including country-pair fixed effects. Tables C.2 and C.6 illustrate that our results remain stable if we connect the grid cell centroids to the network without adding artificial road segments or use the directed network (in which we differentiate between up- and downstream river transportation) to identify least cost paths. Finally, the estimates presented in Table C.11 document that our analysis does not hinge upon the choice of cut off in the ownership definition. We obtain similar results if we define ownership as having a minimum stake of 50% in another firm.

In analogy to the historical analysis, the validity of our findings hinges on the assumption that effective distance captures Roman-era-specific variation in transport costs and is uncorrelated with exogenous factors in the error term that influence the pattern of cross-regional firm ownership today. As before, connectivity within the Roman network has to be unrelated with pre-existing patterns of bilateral economic exchange for this to hold. In Table C.10, we condition on the geography-related connectivity measures introduced in Section 5.1.1. Again, the least-cost route coefficient remains stable throughout, illustrating that there is limited correlation between geography-based least-cost paths and effective distance.

As an indirect way of supporting the Roman-era specificity of our results, we exploit the fact that economic and institutional integration into Roman territory discontinuously changed at the Limes Germanicus. This north-eastern line of defence was directly aimed at monitoring and controlling cross-border trade and information exchange between the Roman Empire and the ‘barbarian’ world. Importantly, the Roman transport network also ended at the Limes and

---

[70] That is, we separately look at business links in which the owner is categorised as belonging to the service and manufacturing industry, respectively.

did not extend across this border. This suggests the existence of a discontinuity at the Limes in terms of transport costs, market access and institutional integration into the Roman Empire. To test whether this is the case, we focus on the areas that lie within 25 kilometres on either side of the Limes[71] and investigate if firm links *across* the vanished border are less common than *within* either side. The results presented in Appendix E unveil that this is the case. Being located on opposite sides of the Limes reduces the number of business links by around 25%. This illustrates that integration into the Roman Empire—of which the incorporation into the transport network was an important (but emphatically not the only) aspect—increases the intensity of current-day bilateral economic interaction. In combination with the absence of a relationship between effective distance and pre-Roman integration (see Section 5.1) and the lack of correlation with geographical least-cost paths, this strongly suggests that our estimates specifically capture consequences induced by the creation of the Roman transport network.

5.2.2 *Extension: business cycle transmission*

Recent evidence documents the importance of cross-border firm ownership—i.e., multinational firms—in explaining international business cycle transmissions (Cravino and Levchenko, 2017). Motivated by these findings, we investigate whether the Roman-era-specific effect on interregional firm ownership is also reflected in more synchronised business cycles. This auxiliary analysis, presented in Appendix D, may add to our understanding of the determinants of interregional contagion of economic shocks. Furthermore, the use of an alternative measure of economic integration (i.e., the intensity of business cycle transmission rather than business links) corroborates the findings presented above.

Absent yearly grid-cell level data on GDP, we employ night-time light intensity as a proxy for regional income and compute the correlation in night-time lights growth between 1992 and 2013 for each grid-cell pair. As shown in Table D.1, income growth fluctuations between regions become less synchronised as connectivity within the Roman transport network decreases. Together with the results of Table 3, this illustrates that the Roman transport network continues to shape today's pattern of interregional economic integration in Western Europe. That is, the intensity of economic interaction between two regions today was (partly) determined by infrastructure investments two millennia ago.

6 Channels connecting Roman connectivity and current integration

Above, we have documented that the Roman transport network shapes today's geography of interregional business links. In the final part of the study, we turn to analysing potential mechanisms underlying this finding. We subsequently focus on four potential channels: (i) persistence in interregional connectivity, and Roman-network-induced similarity in (ii) production structures, (iii) preferences, and (iv) cultural values. In Table 4, we present a range of estimates that aim at investigating the plausibility of these channels and therefore replace the dependent variable in Eq. (1) with proxies for potential mechanisms. To facilitate comparison, the dependent

---

[71] See Appendix E for details on the data construction process and estimation strategy.

variables are standardised with mean zero and a standard deviation of one. Data on preferences are not available for Belgium and Luxembourg, forcing us to restrict the sample to observations that do not feature these countries. Compared to the main analysis (Section 5.2) this reduces our sample size from 731,823 to 671,512 observations.

6.1 Potential channels

A mechanism that potentially generates a direct link between variation in trade costs in the distant past and cross-regional firm ownership patterns today is current connectivity, i.e., regions with stronger ancient connectivity were connected more directly over time. Differences in interregional transport costs that emerged due to the creation of the Roman transport network could still be reflected in the cost of transporting goods and people today. If a firm's investment decision depends on the (relative) accessibility of regions, this would help to explain our previous findings. We provide evidence for the plausibility of this channel using two distinct measures of transport cost. The first is driving distance along the time-minimising route between each pair of grid-cell centroids (extracted from Google Maps), which we interpret as capturing the cost of transporting goods and people using today's road network.[72] This metric reflects variation arising from distance in the road network and differences in the speed of transport associated with different technologies (i.e. motorways, rural roads, etc.). The second measure specifically captures passenger-transport network connectivity. The focus on passenger transport links is motivated by recent studies showing that travel times strongly influence the intensity of cross-regional business connections (Giroud, 2013; Campante and Yanagizawa-Drott, 2018). Minimum travel time—our measure for passenger transport connectivity—between grid-cell-centre pairs is extracted from `rome2rio.com`. Within the multi-modal network, passengers are allowed to use any combination of public transport (bus, train, aeroplane).[73]

Columns (1)–(2) of panel (a) in Table 4 present evidence for persistence in transport network connectivity. The positive and statistically highly significant coefficients document that lower transport costs during Roman times are reflected in greater connectivity within road and passenger transport networks today.Since neither the road or the passenger transport network allows for river or coastal transport, i.e., modes that influenced interregional connectivity during Roman times, this result cannot be interpreted as today's routes tracing Roman routes. Likewise, the finding does not reflect persistence in the layout of the road network. The distance-wise shortest route within the Roman transport network—which predominantly follows roads—does not explain ownership intensity (see Table 3, column 3).[74] The differences between the optimal route within the Roman and today's transport network are illustrated in Figure F.1. Rather, our results suggest that regions with historically stronger ties are connected more directly when new transport technologies became available (e.g., railways, aeroplanes, and highways). Thus, even though past and present transport networks structurally differ in their layout and trans-

---

[72] Today, road transport is the dominant mode of transporting goods within Europe. Trucks carried 76% of the total volume of goods in 2017 (Eurostat, `http://bit.do/ModalSplit`).

[73] We also allow for taxi rides whenever public transport is not available.

[74] As mentioned above, Google driving distance does not capture the shortest distance within the driving distance, but the distance of the time-minimising path. The latter is influenced by distance *and* technology.

port technologies, Roman-era-specific connectivity still explains patterns of bilateral accessibility today.

As a second potential channel, we investigate whether regions better connected within the Roman transport network exhibit more similar production structures. Continued economic interaction could, for example, have resulted in assimilation of industry structures and thereby facilitate cross-regional firm ownership (see Burchardi, Chaney and Hassan, forthcoming). Column (3) indeed indicates that production structures between regions become more dissimilar—as measured by an industry dissimilarity index based on Jaffe (1986)[75]—when bilateral connectivity decreases (i.e., when effective distance increases). The small, albeit significant point estimate implies that industry dissimilarity increases by 0.012 standard deviations when effective distance increases by 10%.

Along with stimulating interregional trade, greater connectivity within the Roman transport network may have affected the flow of migrants, ideas, and culture. This could have led to co-evolution and assimilation of preferences, values, and attitudes in the long run. Greater similarity in these fundamental determinants of economic interaction, in turn, potentially facilitates investment (Guiso, Sapienza and Zingales, 2009; Leblang, 2010; Burchardi, Chaney and Hassan, forthcoming). For example, firms derive a competitive advantage from catering to multiple markets that exhibit a similar demand structure. Furthermore, similarity in preferences and values can reduce information frictions and coordination costs. To investigate whether differential connectivity within the Roman transport network explains variation in preferences and values across space, we draw on geocoded individual-level data from the Global Preference Survey (GPS, Falk et al., 2018) and the European Values Study (EVS, EVS, 2016). To bring the individual-level information to the grid cell level, we first purge the data of country fixed effects and then compute grid-cell-level means by averaging across all respondents that reside within a given cell.[76] We generate measures of cultural similarity across grid-cell pairs by computing the absolute difference in preference and values between any two grid cells. In in Table 4 below, we investigate the influence of effective distance on disparities in individual preferences (panel b) and value categories (panel c) as well as disparity in two aggregate measures of preferences and values derived from principal component analyses (panel a).

Columns (1)–(6) of panel (b) in Table 4 present estimates of effective distance on distance in preferences across grid-cell pairs using the six preferences contained in the GPS: time preference, risk preference, positive and negative reciprocity, altruism, and trust. We find that variation in ancient connectivity explains preference heterogeneity across space in Western Europe. For all but time preference, similarity significantly decreases with effective distance, conditional on Euclidean distance, the full set of grid cell fixed effects as well as the historic and geographic controls (see, e.g., column (2) of Table 3). Column (4) of panel (a) presents results using the first principal component of the six preference distance measures as dependent variable. We find that regions ill-connected within the Roman network exhibit a more dissimilar preference pro-

---

[75] See Appendix F for details.

[76] Note that the most detailed geographical information available on residence of respondents in both surveys is the NUTS 2 level. A detailed description of the data construction process, including the matching of respondents to grid cells, is provided in Appendix F.

Table 4: Channels connecting Roman transport network connectivity and current integration

Panel a: Transport connectivity, production structure, and distance in preferences, values, and attitudes

	ln Google driving distance (SD)	ln Rio2Rome travel time (SD)	Industry dissimilarity (SD)	First principal component preferences (SD)	First principal component attitudes (SD)
	(1)	(2)	(3)	(4)	(5)
ln effective distance	0.125*** (0.009)	0.500*** (0.026)	0.116*** (0.025)	0.152*** (0.021)	0.211*** (0.024)
Raw mean of dep. var.	6.963	6.241	0.800	0	0
SD of raw dep. var.	0.680	0.331	0.161	1.228	1.344
Observations	671,512	671,512	671,512	671,512	671,512
Estimator	OLS	OLS	OLS	OLS	OLS

Panel b: Distance in preferences

	Trust (SD)	Altruism (SD)	Negative reciprocity (SD)	Positive reciprocity (SD)	Risk (SD)	Time (SD)
	(1)	(2)	(3)	(4)	(5)	(6)
ln effective distance	0.048*** (0.018)	0.161*** (0.020)	0.090*** (0.021)	0.052*** (0.012)	0.068*** (0.021)	0.019 (0.018)
Raw mean of dep. var.	0.171	0.151	0.155	0.149	0.153	0.154
SD of raw dep. var.	0.145	0.127	0.122	0.124	0.123	0.126
Observations	671,512	671,512	671,512	671,512	671,512	671,512
Estimator	OLS	OLS	OLS	OLS	OLS	OLS

Panel c: Distance in values and attitudes

	Attitudes and Values towards:					
	Life (SD)	Work (SD)	Religion (SD)	Family (SD)	Politics and society (SD)	Nationalism (SD)
	(1)	(2)	(3)	(4)	(5)	(6)
ln effective distance	-0.017 (0.021)	0.152*** (0.027)	0.140*** (0.027)	0.042** (0.018)	0.059*** (0.013)	0.284*** (0.049)
Raw mean of dep. var.	0.228	0.254	0.278	0.255	0.291	0.355
SD of raw dep. var.	0.183	0.214	0.225	0.225	0.235	0.293
Observations	671,512	671,512	671,512	671,512	671,512	671,512
Estimator	OLS	OLS	OLS	OLS	OLS	OLS

Notes: This table reports estimates of Equation (1) using the OLS estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variables are measures of current-day infrastructure connectivity, industry dissimilarity as well as cultural dissimilarity. They are described in detail in Sections 6 and Appendix F. All regressions control for origin and destination fixed effects, intra-national ownership, shared time under Roman rule, Euclidean distance, and a set of geographic features. For a detailed explanation of the explanatory variables, see Tables 1 and 3. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

file. These results highlight the importance of considering socio-economic forces, in our case the transport-network-induced cumulative history of exchange between regions, when trying to understand why preferences vary across regions. We interpret this finding to indicate that repeated interaction led to the convergence of preferences, which, in turn, facilitates (socio-)economic exchange.

In panel (c) of Table 4, we investigate the relationship of effective distance and distance in attitudes and values constructed using the EVS.[77] Following the structure of the EVS, we categorised the wide range of questions on human values and attitudes into six categories: life, work, religion, family, politics and society, and nationalism.[78] For each category (which consists of a set of multiple questions), we ran a multiple correspondence analysis and computed the row coordinates of the first dimension to simplify the structure of the categorical data and enhance manageability.[79] We find that, except for attitudes towards life, similarity in all categories becomes significantly less aligned with increased effective distance, conditional on Euclidean distance. The largest coefficients are observed for attitudes towards nationalism and views on work. We also find a disparity-increasing impact of effective distance when we use the principal component based on all questions—rather than the six individual topics—as measure for value and attitude dissimilarity (column (5) in panel (a)). These results again illustrate that the origins of heterogeneities in fundamental drivers of economic interactions—in this case values and attitudes—may lie in the creation of new transport infrastructure links that subsequently influence the flow of goods, services, people, and ideas.

6.2 Relative importance of channels

In the final step of our analysis, we assess the relative importance of the channels introduced above. In a horse race specification, we regress the number of business links on effective distance while adding proxies for the various potential mechanisms discussed above. The results are reported in Table 5. In column (1), we run our preferred regression specification (see column (2), Table 3) on the restricted sample. This produces a point estimate of -0.526 which is similar to the one obtained using the full sample (-0.554). Compared to column (1), the size of the effective distance coefficient drops by 29% (column 2) and 36% (column 3) when we account for differences in modern road transport costs and passenger transport accessibility. Combined, the two variables absorb 50% of the Roman transport network coefficient (column 4). This implies that a continued interregional transport infrastructure connectivity is part of the reason why the Roman transport network influences today's spatial firm ownership structure. However, a substantial part of the main effect remains unexplained by this mechanism. As shown in column (5), differences in production structures do not help explain this gap. Compared to column (1), the least-cost route effective distance coefficient remains virtually unchanged when we control for industry similarity.

---

[77] Appendix F provides a description of the data construction process.

[78] See `http://bit.do/evstopics` for a list of the individual questions assigned belonging to each category.

[79] The multiple correspondence analysis can be seen as the counterpart of principal component analysis for categorical data.

Table 5: Accounting for potential channels

Dependent Variable:	Number of Ownership Links (>25% Ownership)								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ln effective distance	-0.526***	-0.372***	-0.338***	-0.261**	-0.523***	-0.426***	-0.374***	-0.348***	-0.160
	(0.111)	(0.111)	(0.109)	(0.111)	(0.111)	(0.101)	(0.102)	(0.100)	(0.101)
ln Driving distance (SD)		-0.890***		-0.612***					-0.439***
		(0.119)		(0.133)					(0.110)
ln Rome2Rio (SD)			-0.286***	-0.241***					-0.204***
			(0.026)	(0.029)					(0.026)
Industry dissimilarity (SD)					-0.149***				-0.136***
					(0.034)				(0.033)
Distance preferences (SD)						-0.383***		-0.264***	-0.212***
						(0.037)		(0.038)	(0.036)
Distance values (SD)							-0.324***	-0.228***	-0.210***
							(0.032)	(0.031)	(0.029)
ln Eucl. distance	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Intra-national ownership	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Joint duration under Roman rule	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geography controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	671,512	671,512	671,512	671,512	671,512	671,512	671,512	671,512	671,512
Estimator	PPML	PPML	PPML	PPML	PPML	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of firms in a cell i that are (part) owned by firms located in grid j. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-national ownership' is a dummy variable that captures whether two grid cells lie within the same country. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Finally, we turn to analysing the importance of preference and value similarity as mediating channels. For ease of exposition, we report specifications in which we add the first principal components rather than the individual preference and value aspects in columns (6)—(8) of Table 5.[80] Including preference disparities into the regression setup reduces the effective distance coefficient by 19% (column 6), while it drops by 29% when differences in attitudes and values are accounted for in column (7). Combined, differences in preferences and values account for 34% of the effective distance coefficient.[81] These findings suggest that the Roman transport network created a new pattern of bilateral interregional (socio-)economic interaction which, over time, led to an increase in preference and value similarity. This, in turn, can (partly) explain variation in cross-regional investment intensity. In the final column of Table 5, we simultaneously add all potential channels. Together, they absorb 70% of the Roman transport network effect on today's spatial firm ownership structure; the effective distance coefficient is no longer statistically significant at conventional confidence levels.

The mechanisms discussed above can thus account for the lion's share of the link between connectivity within the ancient transport network and cross-regional firm investment intensity.

---

[80] In Table F.1, we add all individual measures of preferences and values and attitudes instead of their principal components. The results are qualitatively similar.

[81] As shown in Table F.1, disparities in preferences for reciprocity and risk as well as differing attitudes and values towards life and work exert an (economically) particularly strong negative effect on investment intensity.

However, although insignificant, a non-negligible part of the relationship remains unexplained. We can only speculate about further mechanisms underlying our reduced-form results. These could include variation in genetic distance due to (network-connectivity-induced) historical migration or increasing returns to bilateral relationships. Such channels, while plausibly important in explaining (part) of our results, are inherently hard to measure and can therefore not be included in our analysis. Furthermore, we need to qualify our findings by noting that further research will be necessary to investigate the timing of events. With the data at hand we are unable to understand whether cultural convergence preceded or followed modern infrastructure investment decisions.

7 Conclusion

This paper aimed at analysing the effects of the Roman transport network on economic integration in the past and the present. We document that the creation of the network generated a new pattern of interregional trade within Western Europe that lasted over two millennia. Along with continued economic integration, greater connectivity also led to convergence of values, tastes, and attitudes. This network-induced assimilation in fundamental determinants of economic interaction, in turn, helps to explain patterns of economic interaction today. Similarly, despite the fundamental changes in available transport technologies, today's connectivity patterns reflect ancient connectivity patterns. Business links are much stronger between regions that were better connected within the Roman network, illustrating the long-lasting and multifaceted consequences of infrastructure investments. Current barriers to integration are thus an outcome of historical integration. Therefore, policy makers need to be aware of, and take into account, the long-run consequences of public infrastructure investments. These investments can create or reshape networks in which the transmission of positive and negative shocks is more pronounced.

References

Adams, Collin. 2012. "Transport." In *The Cambridge Companion to the Roman Economy*, edited by Walter Scheidel, 218–240. Cambridge University Press.

Ahern, Kenneth R., Daniele Daminelli, and Cesare Fracassi. 2015. "Lost in Translation? The Effect of Cultural Values on Mergers around the World." *Journal of Financial Economics* 117 (1): 165–189.

Alesina, Alberto, and Nicola Fuchs-Schündeln. 2007. "Goodbye Lenin (or Not?): The Effect of Communism on People's Preferences." *American Economic Review* 97 (4): 1507–1528.

Anderson, James E. 1979. "A Theoretical Foundation for the Gravity Equation." *American Economic Review* 69 (1): 106–116.

Anderson, James E., and Eric van Wincoop. 2003. "Gravity with Gravitas: A Solution to the Border Puzzle." *American Economic Review* 93 (1): 170–192.

Bairoch, Paul. 1990. "The Impact of Crop Yields, Agricultural Productivity and Transport Costs on Urban Growth between 1800 and 1910." In *Urbanization in History: A Process of Dynamic Interactions*, edited by A. M. van der Woude, A. Hayami and Jan De Vries, 134–51. Oxford University Press.

Bakker, Jan David, Stephan Maurer, Jörn-Steffen Pischke, and Ferdinand Rauch. 2018. "Of Mice and Merchants: Trade and Growth in the Iron Age." National Bureau of Economic Research Working Paper 24825.

Baldwin, Richard E., and James Harrigan. 2011. "Zeros, Quality, and Space: Trade Theory and Trade Evidence." *American Economic Journal: Microeconomics* 3 (2): 60–88.

Banerjee, Abhijit, Esther Duflo, and Nancy Qian. 2012. "On the Road: Access to Transportation Infrastructure and Economic Growth in China." National Bureau of Economic Research Working Paper 17897.

Barjamovic, Gojko, Thomas Chaney, Kerem A. Coşar, and Ali Hortaçsu. forthcoming. "Trade, Merchants, and the Lost Cities of the Bronze Age." *The Quarterly Journal of Economics*.

Baum-Snow, Nathaniel, Loren Brandt, J. Vernon Henderson, Matthew A. Turner, and Qinghua Zhang. 2017. "Roads, Railroads, and Decentralization of Chinese Cities." *Review of Economics and Statistics* 99 (3): 435–448.

Benedictow, Ole Jørgen. 2006. *The Black Death, 1346-1353: The Complete History.* Boydell Press.

Berechman, Joseph. 2003. "Transportation-economic Aspects of Roman Highway Development: The Case of Via Appia." *Transportation Research Part A: Policy and Practice* 37 (5): 453 – 478.

Bergstrand, Jeffrey H. 1985. "The Gravity Equation in International Trade: Some Microeconomic Foundations and Empirical Evidence." *Review of Economics and Statistics* 67 (3): 474–481.

Bernard, Andrew B., J. Bradford Jensen, Stephen J. Redding, and Peter K. Schott. 2010. "Intrafirm Trade and Product Contractibility." *American Economic Review* 100 (2): 444–448.

Biraben, Jean-Noël. 1975. *Les Hommes et la Peste en France et dans les Pays Europeens et Mediteraneens.* Mouton.

Boerner, Lars, and Battista Severgnini. 2014. "Epidemic Trade." London School of Economics Economic History Working Papers 212.

Borbála, Maráz. 2006. "Budapest–Gellérthegy és Környékének Késô Latène–Kori TelepüléstörtÉnete Ii." *Budapest Régiségei* 40: 31–44.

Bowman, Alan, and Andrew Wilson. 2009. "Quantifying the Roman Economy: Integration, Growth, Decline?" In *Quantifying the Roman Economy: Methods and Problems*, edited by Alan Bowman and Andrew I. Wilson, 3–86. Oxford: Oxford University Press.

Burchardi, Konrad B., Thomas Chaney, and Tarek A. Hassan. forthcoming. "Migrants, Ancestors, and Foreign Investments." *Review of Economic Studies*.

Burstein, Ariel, Christopher Kurz, and Linda Tesar. 2008. "Trade, Production Sharing, and the International Transmission of Business Cycles." *Journal of Monetary Economics* 55 (4): 775–795.

Campante, Filipe, and David Yanagizawa-Drott. 2018. "Long-Range Growth: Economic Development in the Global Network of Air Links." *The Quarterly Journal of Economics* 133 (3): 1395–

1458.

Campbell, Brian. 2012. *Rivers and the Power of Ancient Rome.* UNC Press Books.

Chaney, Thomas. 2014. "The Network Structure of International Trade." *American Economic Review* 104 (11): 3600–34.

Chen, M. Keith. 2013. "The Effect of Language on Economic Behavior: Evidence from Savings Rates, Health Behaviors, and Retirement Assets." *American Economic Review* 103 (2): 690–731.

Chevallier, Raymond. 1972. *Les Voies Romaines.* Paris: Armond Colin.

Childe, Gordon. 1930. *The Bronze Age.* Cambridge University Press.

Childe, Gordon. 1958. *The Prehistory of European Society.* Penguin Books.

Christakos, George, Ricardo A. Olea, Marc L. Serre, Lin-Lin Wang, and Hwa-Lung Yu. 2005. *Interdisciplinary Public Health Reasoning and Epidemic Modelling: The Case of Black Death.* Springer.

Cipolla, Carlo M. 1974. "The Plague and the Pre-Malthus Malthusians." *Journal of European Economic History* 3 (2): 277–284.

Combes, Pierre-Philippe, Miren Lafourcade, and Thierry Mayer. 2005. "The Trade-Creating Effects of Business and Social Networks: Evidence from France." *Journal of International Economics* 66 (1): 1–29.

Correia, Sergio, Paulo Guimarães, and Thomas Zylkin. 2019. "ppmlhdfe: Fast Poisson Estimation with High-Dimensional Fixed Effects."

Cravino, Javier, and Andrei A. Levchenko. 2017. "Multinational Firms and International Business Cycle Transmission." *The Quarterly Journal of Economics* 132 (2): 921–962.

Cummings, Vicki, Magdalena S. Midgley, and Chris Scarre. 2015. "The Oxford Handbook of Neolithic Europe." edited by Chris Fowler, Jan Harding and Daniela Hofmann, Chapter Chambered Tombs and Passage Graves of Western and Northern Europe. Oxford University Press.

Dalgaard, Carl-Johan, Nicolai Kaarsen, Ola Olsson, and Pablo Selaya. 2018. "Roman Roads to Prosperity: Persistence and Non-Persistence of Public Goods Provision." mimeo.

Dannell, Geoffrey, and Allard W. Mees. 2015. "Getting Samian Ware to Britain: Routes and Transport Possibilities." *Journal of Roman Pottery Studies* 16: 77–92.

Darling, Margaret J. 1998. "Samian from the City of Lincoln: A Question of Status?" In *Form and Fabric. Studies in Rome's material past in Honour of B.R. Hartley*, edited by J. Bird, 169–178. Oxbow Monograph.

Darvill, Timothy. 2013. "The Oxford Handbook of the European Bronze Age." edited by Harry Fokkens and Anthony Harding, Chapter Monuments and Monumentality in Bronze Age Europe. Oxford University Press.

Davies, Hugh E. H. 1998. "Designing Roman Roads." *Britannia* 29: 1–16.

Davis, Donald R. 1995. "Intra-Industry Trade: A Heckscher-Ohlin-Ricardo Approach." *Journal of International Economics* 39: 201–226.

De Benedictis, Luca, Vania M. Licio, and Anna M. Pinna. 2018. "The Long-term Effects of the Historical Roman Road Network: Trade Costs of Italian Provinces." Centre for North

South Economic Research, University of Cagliari and Sassari, Sardinia Working Paper CRENoS 201801.

De Luca, Giuseppe. 2016. "Infrastructure Financing in Medieval Europe." In *Infrastructure Finance in Europe: Insights into the History of Water, Transport, and Telecommunications*, edited by Youssef Cassis, Giuseppe De Luca and Massimo Florio, Chapter 1. OUP Oxford.

de Souza, Philip. 2002. *Piracy in the Graeco-Roman World.* Cambridge University Press.

Dijkstra, Edsger W. 1959. "A Note on Two Problems in Connexion with Graphs." *Numerische Mathematik* 1 (1): 269–271.

Disdier, Anne-Célia, and Keith Head. 2008. "The Puzzling Persistence of the Distance Effect on Bilateral Trade." *Review of Economics and Statistics* 90 (1): 37–48.

Donaldson, Dave. 2018. "Railroads of the Raj: Estimating the Impact of Transportation Infrastructure." *American Economic Review* 108 (4–5): 899–934.

Donaldson, Dave, and Richard Hornbeck. 2016. "Railroads and American Economic Growth: A "Market Access" Approach." *The Quarterly Journal of Economics* 131 (2): 799–858.

Duncan-Jones, Richard. 1974. *The Economy of the Roman Empire. Quantitative Studies.* Cambridge University Press.

Duranton, Gilles, and Matthew A Turner. 2012. "Urban Growth and Transportation." *Review of Economic Studies* 79 (4): 1407–1440.

Duranton, Gilles, Peter M. Morrow, and Matthew A. Turner. 2014. "Roads and Trade: Evidence from the US." *Review of Economic Studies* 81 (2): 681–724.

Eaton, Jonathan, and Samuel Kortum. 2002. "Technology, Geography, and Trade." *Econometrica* 70 (5): 1741–1779.

Eaton, Jonathan, Samuel Kortum, Brent Neiman, and John Romalis. 2016. "Trade and the Global Recession." *American Economic Review* 106 (11): 3401–3438.

Egger, Peter H., and Andrea Lassmann. 2012. "The Language Effect in International Trade: A Meta-analysis." *Economics Letters* 116 (2): 221–224.

Erdkamp, Paul. 2013. "The Food Supply of the Capital." In *The Cambridge Companion to Ancient Rome*, edited by Paul Erdkamp, 262–264. Cambridge University Press.

Estevadeordal, Antoni, and Alan M. Taylor. 2013. "Is the Washington Consensus Dead? Growth, Openness, and the Great Liberalization, 1970s–2000s." *Review of Economics and Statistics* 95 (5): 1669–1690.

EVS. 2016. "European Values Study 2008." 4th wave, Integrated Dataset. GESIS Data Archive, Cologne, Germany, ZA4800 Data File Version 4.0.0.

Faber, Benjamin. 2014. "Trade Integration, Market Size, and Industrialization: Evidence from China's National Trunk Highway System." *Review of Economic Studies* 81 (3): 1046–1070.

Falk, Armin, Anke Becker, Thomas Dohmen, Benjamin Enke, David Huffman, and Uwe Sunde. 2018. "Global Evidence on Economic Preferences." *The Quarterly Journal of Economics* 133 (4): 1645–1692.

Feenstra, Robert C. 2004. *Advanced International Trade: Theory and Evidence.* Princeton University

Press.

Feenstra, Robert C. 2016. *Advanced International Trade: Theory and Evidence.* 2 edition. Princeton, New Jersey: Princeton University Press.

Felbermayr, Gabriel J., and Farid Toubal. 2010. "Cultural Proximity and Trade." *European Economic Review* 54 (2): 279–293.

Feyrer, James. 2009. "Distance, Trade, and Income - The 1967 to 1975 Closing of the Suez Canal as a Natural Experiment." National Bureau of Economic Research Working Paper 15557.

Feyrer, James. forthcoming. "Trade and Income–Exploiting Time Series in Geography." *American Economic Journal: Applied Economics*.

Finley, Moses I. 1999. *The Ancient Economy.* Updated edition by I. Morris edition. University of California Press.

Fitzpatrick, Andrew. 1985. "The Distribution of Dressel 1 Amphorae in Northwest Europe." *Oxford Journal of Archaeology* 4 (3): 305–340.

Flueckiger, Matthias, and Markus Ludwig. 2019. "Transport Infrastructure, Growth and Persistence: The Rise and Demise of the Sui Canal." *Canadian Journal of Economics* 52 (2).

Franconi, Tyler. 2014. "The Economic Development of the Rhine River Basin in the Roman Period (30 BC–AD 406)." PhD diss. Oxford University, UK.

Frankel, Jeffrey A., and David H. Romer. 1999. "Does Trade Cause Growth?" *American Economic Review* 89 (3): 379–399.

Fulford, Michael. 2018. "Procurators' Business? Gallo-Roman Sigillata in Britain in the Second and Third Centuries AD." 301–326.

Furger, Alex, and Sabine Deschler-Erb. 1992. *Das Fundmaterial aus der Schichtenfolge beim Augster Theater: Typologische und osteologische Untersuchungen zur Grabung Theater-Nordwestecke 1986/87.* Römermuseum Augst.

Galor, Oded, and Ömer Özak. 2016. "The Agricultural Origins of Time Preference." *American Economic Review* 106 (10): 3064–3103.

Garcia-López, Miquel-Àngel, Adelheid Holl, and Elisabet Viladecans-Marsal. 2015. "Suburbanization and Highways in Spain When the Romans and the Bourbons Still Shape Its Cities." *Journal of Urban Economics* 85: 52–67.

Garmendia, Aitor, Carlos Llano, Asier Minondo, and Francisco Requena. 2012. "Networks and the Disappearance of the Intranational Home Bias." *Economics Letters* 116 (2): 178–182.

Giroud, Xavier. 2013. "Proximity and Investment: Evidence from Plant-Level Data." *The Quarterly Journal of Economics* 128 (2): 861–915.

Gomtsyan, David. 2017. "The Roman Origins of Modern Migration." mimeo.

Guiso, Luigi, Paola Sapienza, and Luigi Zingales. 2009. "Cultural Biases in Economic Exchange?" *The Quarterly Journal of Economics* 124 (3): 1095–1131.

Hartley, Brian R., Brenda M. Dickinson, Geoffrey B. Dannell, Michael Fulford, Allard W. Mees, Paul Tyers, and Rosemary Wilkinson. 2008. *Names on Terra Sigillata. an Index of Makers' Stamps & Signatures on Gallo-roman Terra Sigillata (Samian Ware).* Vol. 1-9. University of London, Institute of Classical Studies.

Head, Keith, and John Ries. 2008. "FDI as an Outcome of the Market for Corporate Control: Theory and Evidence." *Journal of International Economics* 74(1): 2–20.

Head, Keith, and Thierry Mayer. 2014. "Gravity Equations: Workhorse, Toolkit, and Cookbook." In *Handbook of International Economics*, Vol. 4, edited by Gita Gopinath, Elhanan Helpman and Kenneth S. Rogoff, 131–195. Oxford: Elsevier Ltd.

Hitchner, R. Bruce. 2003. "Roman Empire." In *The Oxford Encyclopedia of Economic History*, Vol. 4, edited by Joel Mokyr, 397–401. Oxford University Press.

Hitchner, R. Bruce. 2012. "Roads, Integration, Connectivity, and Economic Performance in the Roman Empire." In *Highways, Byways, and Road Systems in the Pre-Modern World*, edited by Richard J. A. Talbert Susan E. Alcock, John Bodel, 222–234. Wiley Blackwell.

Holst, Mads Kähler. 2013. "The Oxford Handbook of the European Bronze Age." edited by Harry Fokkens and Anthony Harding, Chapter Burials. Oxford University Press.

Hopkins, Keith. 1980. "Taxes and Trade in the Roman Empire (200 Bc–ad 400)." *The Journal of Roman Studies* 70: 101–125.

Horden, Peregrine, and Nicholas Purcell. 2000. *The Corrupting Sea: A Study of Mediterranean History.* Oxford: Blackwell Publishers.

Hornung, Erik. 2015. "Railroads and Growth in Prussia." *Journal of the European Economic Association* 13 (4): 699–736.

Jaffe, Adam. 1986. "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value." *American Economic Review* 76 (5): 984–1001.

Jedwab, Remi, and Alexander Moradi. 2016. "The Permanent Effects of Transportation Revolutions in Poor Countries: Evidence from Africa." *Review of Economics and Statistics* 98 (2): 268–284.

Jedwab, Remi, Edward Kerby, and Alexander Moradi. 2017. "History, Path Dependence and Development: Evidence from Colonial Railroads, Settlers and Cities in Kenya." *Economic Journal* 127 (603): 1467–1494.

Johnson, Noel D., and Mark Koyama. 2017. "Jewish Communities and City Growth in Preindustrial Europe." *Journal of Development Economics* 127: 339–354.

Jones, Arnold Hugh Martin. 1964. *The Later Roman Empire, 284-602: A Social Economic and Administrative Survey.* Taylor & Francis.

Kessler, David, and Peter Temin. 2008. "Money and Prices in the Early Roman Empire." 137–59. Oxford: Oxford University Press.

Labaune, Yannick, and François Meylan. 2011. "Bibracte Et Autun Au Début De L'époque Romaine: Pour Un Regard Croisé Sur L'urbanisme Et L'architecture." Bibracte.

Laurence, R. 2002. *The Roads of Roman Italy: Mobility and Cultural Change.* Taylor & Francis.

Leblang, David. 2010. "Familiarity Breeds Investment: Diaspora Networks and International Investment." *American Political Science Review* 104 (3): 584–600.

Litina, Anastasia. 2016. "Natural Land Productivity, Cooperation and Comparative Development." *Journal of Economic Growth* 21 (4): 351–408.

Marichal, Robert. 1988. *Les Graffites De La Graufesenque.* Vol. 47. CNRS.

Masschaele, James. 1993. "Transport Costs in Medieval England." *Economic History Review* 46 (2): 266–279.

McWhirr, Alan. 2002. "Transport by Land and Water." In *The Roman World,* Vol. 2, edited by John Wachter, Chapter 26, 658–670. Routledge.

Mees, Allard W. 2011. *Die Verbreitung von Terra Sigillata aus den Manufakturen von Arezzo, Pisa, Lyon und La Graufesenque: Die Transformation der italischen Sigillata-Herstellung in Gallien.* Verlag des Römisch-Germanischen Zentralmuseums.

Mees, Allard W. 2018. "Was There a Difference between Roman 'civil' and 'military' Samian (terra Sigillata) Market Supply? Finding Answers with Statistical Distribution Analysis Methods." *Internet Archaeology* 50.

Melitz, Jacques. 2008. "Language and Foreign Trade." *European Economic Review* 52 (4): 667–699.

Melitz, Jacques, and Farid Toubal. 2014. "Native Language, Spoken Language, Translation and Trade." *Journal of International Economics* 93 (2): 351–363.

Melitz, Marc J. 2003. "The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity." *Econometrica* 71 (6): 1695–1725.

Michaels, Guy. 2008. "The Effect of Trade on the Demand for Skill: Evidence from the Interstate Highway System." *Review of Economics and Statistics* 90 (4): 683–701.

Niblett, Rosalind. 1985. "Sheepen: An Early Roman Industrial Site at Camulodunum (Colchester)." Council for British Archaeology resreport 57, Council for British Arch.

Oxé, August, Howard Comfort, and Philip Kenrick. 2000. *Corpus Vasorum Arretinorum: A Catalogue of the Signatures, Shapes and Chronology of Italian Sigillata.* Vol. 2. Bonn: Habelt.

Özak, Ömer. 2018. "Distance to the Pre-industrial Technological Frontier and Economic Development." *Journal of Economic Growth* 23 (2): 175–221.

Pascali, Luigi. 2017. "The Wind of Change: Maritime Technology, Trade, and Economic Development." *American Economic Review* 107 (9): 2821–54.

Paulsson, B. Schulz. 2019. "Radiocarbon Dates and Bayesian Modeling Support Maritime Diffusion Model for Megaliths in Europe." *PNAS* 116 (9): 3460–3465.

Percoco, Marco. 2015. "Highways, Local Economic Structure and Urban Development." *Journal of Economic Geography* 16 (5): 1035–1054.

Polak, M. 1998. "Old Wine in New Bottles. Reflections on the Organization of the Production of Terra Sigillata at La Graufesenque." 115–122. Oxbow Books.

Polak, Marinus. 2000. *South Gaulish Terra Sigillata with Potters' Stamps from Vechten.* Nijmegen: Katholieke Universiteit Nijmegen.

Portes, Richard, and Helene Rey. 2005. "The Determinants of Cross-border Equity Flows." *Journal of International Economics* 65 (2): 269–296.

Rathmann, Michael. 2003. *Untersuchungen zu den Reichsstraßen in den westlichen Provinzen des Imperium Romanum.* Vol. 55. Mainz: von Zabern.

Rauch, James E. 1999. “Networks versus Markets in International Trade.” *Journal of International Economics* 48 (1): 7–35.

Rauch, James E., and Vitor Trindade. 2002. “Ethnic Chinese Networks in International Trade.” *Review of Economics and Statistics* 84 (1): 116–130.

Reddé, Michel. 2018. “The Impact of the German Frontier on the Economic Development of the Countryside of Roman Gaul.” *Journal of Roman Archaeology* 31: 131–160.

Redding, Stephen J., and Matthew A. Turner. 2015. “Transportation Costs and the Spatial Organization of Economic Activity.” In *Handbook of Regional and Urban Economics*, Vol. 5, edited by Gilles Duranton, J. Vernon Henderson and William C. Strange, 1339–1398. Elsevier.

Redding, Stephen J., Daniel M. Sturm, and Nikolaus Wolf. 2011. “History and Industry Location: Evidence from German Airports.” *Review of Economics and Statistics* 93 (3): 814–831.

Römisch-Germanisches Zentralmuseum in Mainz. “`http://www.rgzm.de/samian/`.”

Santos Silva, João M.C., and Silvana Tenreyro. 2006. “The Log of Gravity.” *Review of Economics and Statistics* 88 (4): 641–658.

Scheidel, Walter. 2014. “The Shape of the Roman World: Modelling Imperial Connectivity.” *Journal of Roman Archaeology* 27: 7–32.

Schmidts, Thomas. 2011. *Akteure und Organisation der Handelschifffahrt in den nordwestlichen Provinzen des Römischen Reiches.* Verlag des Römisch-Germanischen Zentralmuseums.

Sidebotham, Steven E. 1986. *Roman Economic Policy in the Erythra Thalassa: 30 B.C.-A.D. 217. Mnemosyne , Vol Suppl. 91*. University Microfilms.

Storeygard, Adam. 2016. “Farther on Down the Road: Transport Costs, Trade and Urban Growth in Sub-saharan Africa.” *Review of Economic Studies* 83 (3): 1263–1295.

Tabellini, Guido. 2008. “Institutions and Culture.” *Journal of the European Economic Association* 6 (2-3): 255–294.

Talbert, Richard, and Roger Bagnall. 2000. *Barrington Atlas of the Greek and Roman World.* Princeton, N.J.: Princeton University Press.

Temin, Peter. 2012. *The Roman Market Economy.* Princeton University Press.

van Enckevort, Harry, and Jan Thijssen. 2009. “Der Hauptort der Bataver in Nijmegen im 1. Jahrhundert n. Chr. – Von Batavodurum und Oppidum Batavorum nach Ulpia Noviomagus.”

Wacziarg, Romain, and Karen Horn Welch. 2008. “Trade Liberalization and Growth: New Evidence.” *The World Bank Economic Review* 22 (2): 187–231.

Wahl, Fabian. 2017. “Does European Development Have Roman Roots? Evidence from the German Limes.” *Journal of Economic Growth* 22 (3): 313–349.

Weber, Meike. 2012. “The Devil is in the (Samian) Detail–Potters’ Stamps on Samian Ware and their Implications for the Roman Provincial Economy.” *Theoretical Roman Archaeology Journal* 2011: 60—75.

Whittaker, Charles Richard. 1994. *Frontiers of the Roman Empire: A Social and Economic Study.* Baltimore: Johns Hopkins University Press.

Willis, Steven. 2005. “Samian Pottery, a Resource for the Study of Roman Britain and beyond:

The Results of the English Heritage Funded Samian Project. an E-monograph." *Internet Archaeology* 17.

Wilson, Andrew I. 2009. "Large-scale Manufacturing, Standardization, and Trade." In *The Oxford Handbook of Engineering and Technology in the Classical World*, edited by John Peter Oleson, 393–417. Oxford: Oxford University Press.

Wilson, Andrew I., and Alan K Bowman. 2018. *Trade, Commerce, and the State in the Roman World.* Oxford University Press.

Wolf, Nikolaus. 2009. "Was Germany Ever United? Evidence from Intra- and International Trade, 1885–1933." *Journal of Economic History* 69 (3): 846–881.

Yeo, Cedric A. 1946. "Land and Sea Transportation in Imperial Italy." *Transactions and Proceedings of the American Philological Association* 77: 221–244.

Appendices

A Data and summary statistics

A.1 Sources for navigable river sections

Table A.1: Sources for navigable river sections

River	Navigable until:	Source:
Adour	Saint-Sever	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Alb	Ettlingen	Archäologisches Landesmuseum Baden-Württemberg (2006, p. 419)
Allier	Clermont-Ferrand	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Anas	Augusta Emerita	De Soto (2013*a*), Carreras Monfort and De Soto (2009*a*, pp. 303–324), Garcia (1982)
Arno	Arezzo	Campbell (2012, p. 300)
Arroux	near Autun	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Aude (Atax)	Narbonne	Pasquini and Petit (2016, p. 22)
Baetis	Castulo	Munoz (1997, pp. 125–147), De Soto (2013*a*)
Cher	Chateauneuf-sur-Cher	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Colne River	Colchester	Campbell (2012, p. 289)
Deva	fully navigable	De Soto (2013*b*)
Donau	Rißtissen	Archäologisches Landesmuseum Baden-Württemberg (2006, p. 419)
Dordogne	Bergerac	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Doubs	Vesontio	Campbell (2012, p. 69), Moret (2015, Fig 6)
Drava	Klagenfurt	Campbell (2012, p. 292)
Durius	Barca d'Alva (Portugal)	García y Bellido (1944, p. 511), Parodi Álvarez (2012, pp. 137–156)
Ebro	Vareia (Logroño)	Carreras Monfort and De Soto (2009*a*, pp. 303–324), De Soto (2013*b*)
Enz	Pforzheim	Eckoldt (1983, p. 16)
Foss Dyke	Between Trent-River (Torksey) and Witham-River (Lincoln)	Cumberlidge (2009, pp. 120–121), Campbell (2012, p. 289)
Garonne (Garumna)	D'Auterive (just south of Toulouse)	Latour (2006, p. 47)
Inn	Hall	Gattermayr and Steck (2006, p. 7)
Jll	Colmar	Campbell (2012, p. 280), Eckoldt (1986, p. 62)
Limia	fully navigable	García y Bellido (1944, p. 511)
Loir	Chateau-Du-Loir	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Loire (Liger)	Roanne	Williams and Boone (2002, p. 11)
Maenuba	fully navigable	Munoz (1997, pp. 125–147), De Soto (2013*a*)
Main	Mainz	Archäologisches Landesmuseum Baden-Württemberg (2006, p. 388)
Marne	near Saint Dizier	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Mayenne	Mayenne	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Meuse (Mosa)	fully navigable	Wightman (1985, p. 152)
Minius	Lucus Augusti (Lugo)	De Soto (2013*b*)
Mondego River	fully navigable	Parodi Álvarez (2012, pp. 137–156)
Moselle (Mosella)	Epinal	Pasquini and Petit (2016, p. 28)
Nahe	Idar-Oberstein	Dannell and Mees (2015, p. 78)
Neckar	Fischingen	Eckoldt (1983, p. 15)
Nervion	fully navigable	De Soto (2013*b*)
Oise	Tergnier	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Ouse River	York	Campbell (2012, p. 289)
Po	Lago Di Maggiore	Campbell (2012, p. 302)
Rhein	Augusta Raurica (Augst)	Campbell (2012, p. 282)
Rhone	Confluence with Saone at Lugdunum	Campbell (2012, p. 263)
Saar	Saarbrücken	Dannell and Mees (2015, p. 78)

Saone (Arar)	Dijon	Campbell (2012, p. 268)
Sarthe	Le Mans	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Sava	Jesenice	Campbell (2012, p. 292)
Schelde	Valenciennes	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Segre	from Ebro until Balaguer	Carreras Monfort and De Soto (2008/2009*b*, pp. 313–333)
Seine (Sequana)	near Paris (confluence with Marne)	Campbell (2012, p. 265)
Severn	Gloucester	Campbell (2012, p. 289)
Sil	fully navigable	De Soto (2013*b*)
Tagus	Aranjuey	Carreras Monfort and De Soto (2009*a*, pp. 303–324), García y Bellido (1944, p. 511)
Tarn	near Montauban	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Themse	London	Campbell (2012, p. 289)
Tiber	Città di Castello	Campbell (2012, pp. 309–320)
Trent River	Torksey	Campbell (2012, p. 206 & 289), Cumberlidge (2009, p. 120-121)
Turia	fully navigable	Burriel Alberich, Ribera i Lacomba and Serrano Marco (2004, pp. 129–137)
Vienne	near Limoges	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Villaine	Rennes	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)
Witham River	Lincoln	Cumberlidge (2009, pp. 120–121)
Yonne	Sens	Dannell and Mees (2015, Fig 1), Moret (2015, Fig 6)

A.2 Terra sigillata

Table A.2: Production sites and total quantities

Production Site	Quantity of Terra Sigillata	Production Site	Quantity of Terra Sigillata
Arezzo	15644	Les Allieux	190
Aspiran	82	Les Martres-de-Veyre	5156
Avocourt	248	Lezoux	54992
Banassac	1030	Lot Valley	8
Blickweiler	2066	Luxeuil	4
Boucheporn	192	Lyon	2512
Cales	28	Marseille	2
Carrade	86	Montans	5170
Chémery-Faulquemont	2568	Mougon	2
Colchester	284	Ostia	4
Crambade	4	Pfaffenhofen	58
Cremona	32	Pisa	7886
Eschweilerhof	64	Pulborough	22
Espalion	50	Rheinzabern	26536
Faenza	10	Scoppieto	406
Haute-Yutz	32	Torrita di Siena	114
Heiligenberg	1966	Toulon-sur-Allier	388
Ittenwiller	286	Trier	4612
Jaulges-Villiers-Vineux	18	Vasanello	460
Kräherwald	78	Vichy (Terre-Franche)	2
La Graufesenque	150378	Vienne	36
La Madeleine	4566	Waiblingen-Beinstein	70
Lavoye	1112	Westerndorf	290
Le Rozier	482		

Notes: *Quantity of Terra Sigillata* represents the total number of terra sigillata finds produced at a given site and excavated within the area covered by our sample, i.e., Western Europe excluding within grid-cell finds.

A.3 Freight rates derived from Diocletian's Price Edict

Calculations for relative freight rates during the Roman era are based on Diocletian's Price Edict. The Edict was published in 301 CE by the Roman Emperor Diocletian (reign 286–305 CE) and is considered one of the most comprehensive pieces of legislation surviving from Antiquity. The edict is divided into one part explaining its intention and a second part listing approximate 1,400 prices for goods and services. The listed prices constitute price ceilings that aimed at stabilizing the Roman economy and preventing rent seeking of traders and 'profiteers' (Duncan-Jones, 1982, p. 367). Frequent debasement of the currency by preceding emperors had facilitated inflation and the crisis of the third century during which the empire nearly collapsed. The prices ceilings had little impact until the end of Diocletian's reign in 305 CE. The edict lists the maximum price of land transport by wagon at 20 denarii for transporting 1,200 pounds of wheat per Roman mile, amounting to costs of 0.035 denarii per kg and mile. Downstream river transport is listed at 1 denarius per 20 Roman miles (0.0034 denarii per kg and mile), whereas upstream river transport is listed at 2 denarii (0.0068 denarii per kg and mile). Furthermore, the edict includes freight charges for shipping on 51 sea-routes between specific destinations. Scheidel (2013) lists 48 connections with a clearly identifiable start- and end-point for which he calculates travel distances using the ORBIS: The Stanford Geospatial Network Model of the Roman World (see http://orbis.stanford.edu/?). The resulting distances yield a mean price of

0.00067 denarii per kg of wheat per mile. Once normalized to the cost of sea travel, average transport costs per kg of wheat per mile assume a ratio of 1 (sea), 5 (downstream river), 10 (upstream river), 52 (road). By using relative instead of absolute prices, we avoid issues arising from wrongly inferring the price levels as discussed in the literature. Historians generally agree that the relative costs are informative about freight rates during the Roman Empire (Scheidel, 2014; Hopkins, 1983). Scheidel (2013) also calculates the travel duration in days for each of the 48 sea connections. After finding a strong correlation between the listed price and the travel time, he concludes that the Edict has a high level of reliability and internal consistency. [82]

---

[82] For example, the quote for freight rates for maritime transport between Alexandria and Rome is 16 denarii, for a journey is calculated to have taken 17.7 days. The quote for maritime transport between Byzantium and Rome is 18 denarii, for a journey is calculated to have taken 19.4 days.

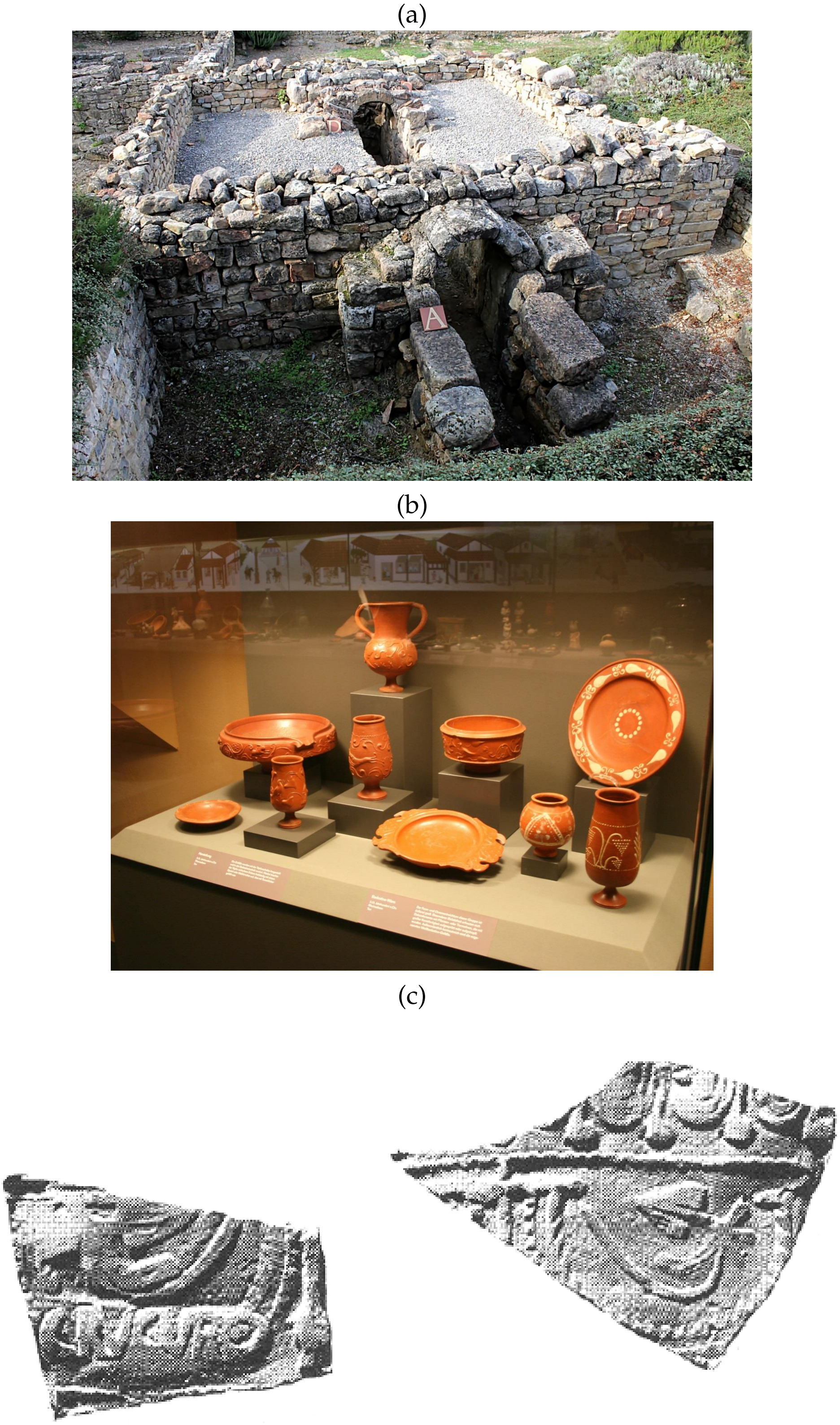

Figure A.1: Production and Design of Roman Terra Sigillata
Panel (a) shows a kiln at La Graufesenque. Panel (b) depicts a variety of terra sigillata products produced at the Rheinzabern site. Panel (c) shows a stamped potsherd that was produced at La Graufesenque and excavated in Kaiseraugst (Switzerland) (source: `https://www1.rgzm.de/samian`).

A.4 Summary statistics

Table A.3: Descriptive statistics of key variables

Variable	Mean	Std. dev.	Min.	Max.	Obs.
	Historical Sample				
Number of terra sigillata finds	10.040	153.291	0	11768	20,125
ln effective distance	9.327	0.457	6.503	10.432	20,125
ln Euclidean distance	6.578	0.682	3.687	7.867	20,125
ln network distance	13.538	0.628	10.635	14.805	20,125
Joint duration under Roman rule	4.316	0.634	3.570	6.720	20,125
Absolute distance latitude	4.073	2.956	0	15.483	20,125
Same biome	0.297	0.457	0	1	20,125
Same waterway	0.281	0.450	0	1	20,125
Both Mediterranean Sea	0.009	0.095	0	1	20,125
	Current-Day Sample				
Number of ownership links	0.146	3.482	0	1225	731,823
Effective distance	9.421	0.477	5.953	10.657	731,823
Euclidean distance	6.842	0.700	3.060	8.039	731,823
ln network distance	13.823	0.647	10.324	14.950	731,823
Intra-national ownership	0.184	0.388	0	1	731,823
Joint duration under Roman rule	4.410	0.697	3.570	6.720	731,823
Absolute distance latitude	5.101	3.664	0	18.457	731,823
Same biome	0.291	0.454	0	1	731,823
Same waterway	0.143	0.351	0	1	731,823
Both Mediterranean Sea	0.016	0.126	0	1	731,823

B Data construction economic integration in post-Roman era

Price correlation

The measures for grid-cell-pair-level price correlation are constructed using the Allen-Unger Global Commodity Prices Database (see http://mdr-maa.org/resource/allen-unger-global-commodity-prices-database/?). This data source spans the time period from the central middle ages to the 20th century and contains information on prices for a great variety of food, drink, raw materials, and manufactured goods. We identify all prices prior to 1790 that can be mapped to specific location (i.e., a city) that lies within Western Europe. This leaves us with 80 cities, 38 different commodities and a total of 463,786 city-commodity pairs. We then compute the price correlation for each commodity-city pair. Next we determine into which grid cells the cities fall and compute the average price correlation for each grid cell pair, whereby we weight the individual correlations by the number of observations it is based on. Our final grid-cell-pair-level dataset consists of 1,676 price correlations (1,518 observations when restricted to wheat prices).

Plague data

City-level data on the date of the first recorded case of the Black Death are extracted from Christakos et al. (2005, pp. 214–282), who compile their dataset from a wide range of historical sources. We manually geocoded the location of all cities in the database for which we can determine the

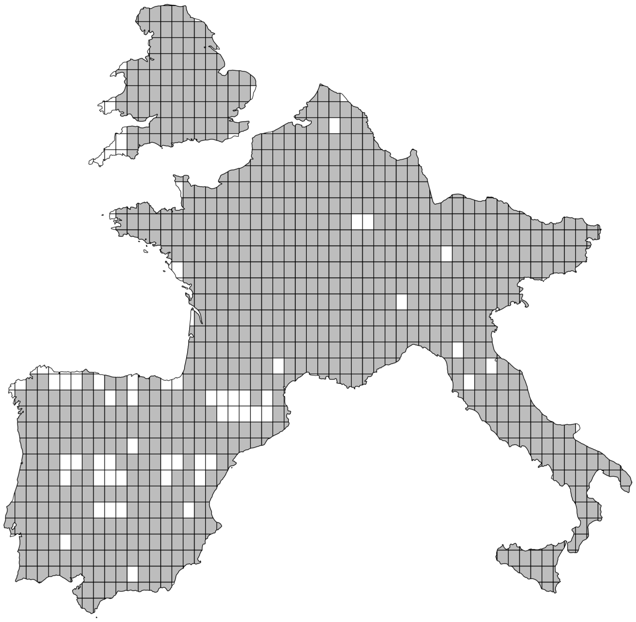

Figure A.2: Extensive Margin of Connectivity to the Roman Transport Network
Figure depicts grid cells intersected by the Roman transport network (shaded grey).

month and year in which the Black Death arrived. For each city, we identified which 0.5×0.5 degree grid cell it falls into.[83] The measure for the time lag in onset of the epidemic between two grid cells—*i* and *j*—is constructed in the following way: First, we compute the time lag in onset of the Black Death (measured in months) between each city located in grid cell *i* and each city located in grid cell *j*. In a second step, we take the average of these lags to obtain a measure for the differential timing of the onset at the grid-cell-pair level.

---

[83] This leaves us with 282 cities, which fall into 217 grid cells.

C Robustness and falsification

C.1 Connecting the centroid to the network

We connect a grid cell to the Roman transport network by creating an artificial straight-line road segment between its centroid and the closest point on the intersecting network leg(s).[84] On average, the artificial road segments make up 7% of the total transport costs. Variation in the length of the added road segment—more precisely the associated costs—represents the fact that average distance to the network varies substantially across grid cells.

Figure C.1 illustrates the connecting procedure for two grid cells—located in central France—with differential access to the network. Grid cell (b) is only intersected at the edge. Hence, average distance from points within this cell to the network is large. Conversely, multiple segments of the network cut across cell (a), including one near its centre; average distance to the network is thus much shorter.

Figure C.1: Connecting Centroids to the Roman Transport Network
Panel (a) depicts two exemplary grid cells in which artificial straight-line road segments (dashed lines) were added to connect centroids to the Roman transport network. Panel (b) shows location of the two grid cells in France.

It is important to note that our results are not dependent on the choice of how to connect grid cells to the transport network. The estimates are robust to the use of alternative connection procedures. This is illustrated in Tables C.1–C.2 below, where we connect centroids to the network without imposing any costs.[85]

---

[84] Note that all grid cells in our sample are intersected by the network. However, there are substantial differences in the number, location, and type (road, river, sea) of legs that cut across the individual cells. The inclusion of origin and destination fixed effects accounts for such differences.

[85] That is, the transport costs along the artificial road segments are assumed to be zero.

Table C.1: Connecting to the network without addition of artificial road segment: Roman transport network and trade during Roman era

Dependent Variable:	Number of Terra Sigillata Finds				
	(1)	(2)	(3)	(4)	(5)
ln effective distance	-2.125***	-1.621***	-1.895***	-0.809***	-1.207***
	(0.355)	(0.360)	(0.348)	(0.289)	(0.299)
Joint duration under Roman rule (centuries)		2.717***	2.248***	1.469*	1.750**
		(0.619)	(0.630)	(0.765)	(0.680)
ln Eucl. distance				-1.056***	
				(0.287)	
ln network distance					-0.824***
					(0.195)
Geography controls	No	No	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes
Observations	20,125	20,125	20,125	20,125	20,125
Estimator	PPML	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of Terra Sigillata finds in a cell i that originates from cell j. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'network distance' measures the length in kilometres of the distance-wise shortest path between grid cell centroids within the Roman transport network. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C.2: Connecting to the network without addition of artificial road segment: Roman transport network and interregional firm ownership

Dependent Variable:	Number of Ownership Links (>25% Ownership)				
	Full Sample			Manufacturing	Service
	(1)	(2)	(3)	(4)	(5)
ln effective distance	-0.505*** (0.083)	-0.467*** (0.087)	-0.426*** (0.098)	-0.491*** (0.079)	-0.434*** (0.143)
ln Eucl. distance	-1.172*** (0.067)	-1.229*** (0.075)	-1.132*** (0.130)	-1.285*** (0.076)	-0.882*** (0.115)
Intra-national ownership	1.253*** (0.110)	1.125*** (0.125)	1.117*** (0.126)	1.001*** (0.116)	1.557*** (0.150)
Joint duration under Roman rule (centuries)		0.575*** (0.155)	0.574*** (0.155)	0.624*** (0.151)	0.400* (0.223)
ln network distance			-0.150 (0.151)		
Geography controls	No	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes
Observations	731,823	731,823	731,823	602,597	470,736
Estimator	PPML	PPML	PPML	PPML	PPML

This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of firms in a cell i that are (part) owned by firms located in grid j. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-national ownership' is a dummy variable that captures whether two grid cells lie within the same country. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'network distance' measures the number of kilometres of the distance-wise shortest path between grid cell centroids within the Roman transport network. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

C.2 Roman trade network and pre-Roman interaction

Table C.3: Pre-Roman interaction

Dependent variable:	Both Grids Cells Dolmen (Megalithic)[a]	Both Grid Cells Chambered Cairns (Megalithic)[b]	Both Grid Cells Round Barrows (Tumulus)[c]	Both Grid Cells Oppida[d]
	(1)	(2)	(3)	(4)
ln effective distance	-0.003	0.002	0.001	-0.002
	(0.008)	(0.001)	(0.003)	(0.002)
ln Eucl. distance	-0.092***	-0.003***	-0.011***	-0.006***
	(0.008)	(0.001)	(0.003)	(0.002)
Mean dep. var.	0.144	0.002	0.030	0.0115
Destination FEs	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes
Geography controls	Yes	Yes	Yes	Yes
Observations	368,070	368,070	368,070	368,070
Estimator	OLS	OLS	OLS	OLS

Notes: This table reports estimates of Equation (1) using the OLS estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

[a] LHS variable is an indicator that takes the value one if both grid cells are characterised by the presence of at least one burial chamber. Data source: `http://bit.do/burialchambers`.

[b] LHS variable is an indicator that takes the value one if both grid cells are characterised by the presence of at least one chambered cairn. Data source: `http://bit.do/chamberedcairns`.

[c] LHS variable is an indicator that takes the value one if both grid cells are characterised by the presence of at least one round barrow. Data source: `http://bit.do/roundbarrows`.

[d] LHS variable is an indicator that takes the value one if both grid cells are characterised by the presence of at least one Celtic oppidum. Data source: `http://bit.do/oppida`.

C.3 Production-site-level analysis

Table C.4: Roman transport network and trade during Roman era

Dependent Variable:	Number of Terra Sigillata Finds				
	(1)	(2)	(3)	(4)	(5)
ln effective distance	-2.357***	-1.786***	-2.106***	-0.933***	-1.365***
	(0.387)	(0.411)	(0.384)	(0.361)	(0.351)
Joint duration under Roman rule(centuries)		2.616***	2.149***	1.420*	1.682**
		(0.638)	(0.653)	(0.768)	(0.688)
ln Eucl. distance				-1.040***	
				(0.298)	
ln network distance					-0.803***
					(0.202)
Geography controls	No	No	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes
Origin-production site FEs	Yes	Yes	Yes	Yes	Yes
Observations	23,479	23,479	23,479	23,479	23,479
Estimator	PPML	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of Terra Sigillata finds in a cell i that originates from cell j (excluding within 'production site' grid cell finds). 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'network distance' measures the length in kilometres of the distance-wise shortest path between grid cell centroids within the Roman transport network. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

C.4 Least-cost route using a directed network

Table C.5: Directed transport network: Roman transport network and trade during Roman era

Dependent Variable:	Number of Terra Sigillata Finds				
	(1)	(2)	(3)	(4)	(5)
ln directed effective distance	-2.267***	-1.688***	-2.141***	-0.930***	-1.369***
	(0.417)	(0.428)	(0.399)	(0.353)	(0.350)
Joint duration under Roman rule		2.717***	2.139***	1.417*	1.683**
		(0.638)	(0.645)	(0.763)	(0.683)
ln Eucl. distance				-1.049***	
				(0.296)	
ln network distance					-0.800***
					(0.191)
Geography controls	No	No	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes
Observations	20,125	20,125	20,125	20,125	20,125
Estimator	PPML	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of Terra Sigillata finds in a cell i that originates from cell j. 'Directed effective distance' represents the cost associated with shipping goods along the least cost path given the directed Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'network distance' measures the length in kilometres of the distance-wise shortest path between grid cell centroids within the Roman transport network. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C.6: Directed transport network: Roman transport network and interregional firm ownership

Dependent Variable:	Number of Ownership Links (>25% Ownership)				
	Full Sample			Manufacturing	Service
	(1)	(2)	(3)	(4)	(5)
ln directed effective distance	-0.625***	-0.569***	-0.516***	-0.583***	-0.698***
	(0.100)	(0.108)	(0.117)	(0.100)	(0.168)
ln Eucl. distance	-1.166***	-1.231***	-1.122***	-1.287***	-0.815***
	(0.073)	(0.080)	(0.128)	(0.076)	(0.127)
Intra-national ownership	1.225***	1.113***	1.104***	0.991***	1.571***
	(0.110)	(0.124)	(0.126)	(0.116)	(0.148)
Joint duration under Roman rule (centuries)		0.530***	0.532***	0.586***	0.315
		(0.159)	(0.160)	(0.154)	(0.228)
ln network distance			-0.167		
			(0.144)		
Geography controls	No	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes
Observations	731,823	731,823	731,823	602,597	470,736
Estimator	PPML	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of firms in a cell i that are (part) owned by firms located in grid j. 'Directed effective distance' represents the cost associated with shipping goods along the least cost path given the directed Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-national ownership' is a dummy variable that captures whether two grid cells lie within the same country. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'network distance' measures the number of kilometres of the distance-wise shortest path between grid cell centroids within the Roman transport network. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

C.5 Additional controls, clustering approach, and margins of trade

Table C.7: Robustness: Roman transport network and trade during Roman era

Dependent Variable:	Number of Terra Sigillata Finds			
	(1)	(2)	(3)	(4)
ln effective distance	-0.751*** (0.240)	-0.895** (0.397)	-0.754** (0.325)	-0.140*** (0.036)
Robustness	additional controls	clustering	intensive margin	extensive margin
Joint duration under Roman rule	Yes	Yes	Yes	Yes
ln Eucl. distance	Yes	Yes	Yes	Yes
Geography controls	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes
Observations	20,125	20,125	1,966	20,125
Estimator	PPML	PPML	PPML	OLS

Notes: This table reports estimates of Equation (1). Columns (1)–(3) estimated by PPML, column (4) by OLS. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses (columns (1), (3)-(4)) and two-way clustered at the respective 1 × 1 degree super grids (column (2)). Dependent variable is the count of Terra Sigillata finds in a cell *i* that originates from cell *j*. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. Geography controls described in notes of Table 1. The set of additional controls consists of the absolute distance in longitude, elevation, ruggedness, agricultural suitability, precipitation and temperature.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C.8: Robustness Roman transport network and interregional firm ownership

Dependent Variable:	Number of Ownership Links (>25% Ownership)				
	(1)	(2)	(3)	(4)	(5)
ln effective distance	-0.495*** (0.110)	-0.349*** (0.104)	-0.554*** (0.133)	-0.472*** (0.093)	-0.094*** (0.006)
Robustness	additional controls	clustering	country-pair FE	intensive margin	extensive margin
Joint duration under Roman rule	Yes	Yes	Yes	Yes	Yes
Intra-national ownership	Yes	Yes	Yes	Yes	Yes
ln Eucl. distance	Yes	Yes	Yes	Yes	Yes
Geography controls	Yes	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes
Observations	731,823	731,823	731,823	731,823	24,149
Estimator	PPML	PPML	PPML	PPML	OLS

Notes: This table reports estimates of Equation (1). Columns (1)–(4) estimated by PPML, column (5) by OLS. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses (columns (1), (3)-(5)) and two-way clustered at the respective 1 × 1 degree super grids (column (2)). Dependent variable is the count of firms in a cell *i* that are (part) owned by firms located in grid *j*. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-national ownership' is a dummy variable that captures whether two grid cells lie within the same country. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. Geography controls described in notes of Table 1. The set of additional controls consists of the absolute distance in longitude, elevation, ruggedness, agricultural suitability, precipitation and temperature. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

C.6 Geography-based least-cost measures

An important assumption underlying our identification strategy is that the least-cost path effective distance captures Roman-era-specific variation in bilateral transport costs. This assumption may be violated if connectivity within the Roman network is driven by geographical features.[86] In this case, the effective distance coefficient would not (only) capture Roman-era-specific effects but also general, Roman era unrelated, differences in transport costs. As a consequence, estimates would be biased.

In this section, we show that correlation with geographically optimal transport routes is an unlikely source of bias. To this end, we construct two alternative, Roman-era unspecific, measures of bilateral connectivity and document that our estimates remain stable when they are included in the regression. The first distance measure is the Human Mobility Index with Seafaring (HMISea) developed in Özak (2018).[87] The HMISea represents a measure of travel time in the pre-industrial era and takes human biological constraints as well as geographical and technological factors into account.[88]

The second connectivity measure is constructed based on geographical features alone. Using 1km×1km gridded elevation data from Hijmans et al. (2005), we first compute the horizontal distance between any two contiguous grid cells as well as the (signed) difference between them. We then translate this information into travel time (measured in seconds) by applying the formula of Langmuir (2003, pp. 39 ff.). If cells are connected by rivers, lakes or sea, we assume that crossing time is 10% faster than over a featureless plain overland (similar to Barjamovic et al., forthcoming).[89] Given this transition cost raster, we then determine the cost of travelling between any two centroids across the 0.5×0.5 grid cells (which form the basis of our empirical analysis) by applying Dijkstra (1959)'s algorithm.[90]

Tables C.9–C.10 document the stability of our result with respect to the inclusion of the two alternative connectivity measures. In column (1) of Table C.9, we reproduce the regression of bilateral trade flows during the Roman era on effective distance in our preferred specification (column 4, Table 1). Compared to this baseline estimate, the least-cost route coefficient remains qualitatively similar when we successively control for the two alternative distance measures in columns (2)–(3). This is also the case when we simultaneously include all measures as controls (column 4).

In Table C.10, we investigate the robustness of our current-era estimates. Reassuringly, the effective distance coefficient obtained from our preferred specification (column 1) changes only slightly when we account for alternative least-cost measures (columns 2–4).

---

[86] Roads, for example, could follow geographically optimal paths.

[87] We are grateful to Ömer Özak for providing us with the data.

[88] See Özak (2010) and Özak (2018, p. 191), for a detailed description of the index.

[89] Data on location of water bodies are taken from `www.naturalearthdata.com`.

[90] The results remain very stable if we increase the level of aggregation at which the least cost routes are computed. Specifically, we additionally computed the optimal paths using elevation data aggregated at the 10×10 km and 50×50 km level.

Table C.9: Robustness alternative connectivity: Roman transport network and trade during Roman era

	Number of Terra Sigillata Finds			
Least cost path controlled for	None	HMISea Özak (2018)	Langmuir (2003)	All
	(1)	(2)	(3)	(4)
ln effective distance	-0.943*** (0.358)	-0.873*** (0.316)	-0.867*** (0.319)	-0.887*** (0.340)
ln Eucl. distance	Yes	Yes	Yes	Yes
Geography controls	Yes	Yes	Yes	Yes
Joint duration under Roman rule	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes
Observations	20,125	20,125	20,125	20,125
Estimator	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of Terra Sigillata finds in a cell i that originates from cell j. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. Geography controls described in notes of Table 1. Least cost paths described in detailed in Section C.6 above. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C.10: Robustness alternative connectivity: Roman transport network and interregional firm ownership

	Number of Ownership Links (>25% Ownership)			
Least cost path controlled for	None	HMISea Özak (2018)	Langmuir (2003)	All
	(1)	(2)	(3)	(4)
ln effective distance	-0.554*** (0.109)	-0.579*** (0.105)	-0.371*** (0.111)	-0.463*** (0.105)
ln Eucl. distance	Yes	Yes	Yes	Yes
Intra-national ownership	Yes	Yes	Yes	Yes
Joint duration under Roman rule	Yes	Yes	Yes	Yes
Geography controls	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes
Observations	731,823	731,823	731,823	731,823
Estimator	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of firms in a cell i that are (part) owned by firms located in grid j. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-national ownership' is a dummy variable that captures whether two grid cells lie within the same country. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. Geography controls described in notes of Table 1. Least cost paths described in detailed in Section C.6 above. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

C.7 Alternative ownership definition

Table C.11: Alternative definition (>50% ownership): Roman transport network and interregional firm ownership

Dependent Variable:	Number of Ownership Links (>50% Ownership)				
	Full Sample			Manufacturing	Service
	(1)	(2)	(3)	(4)	(5)
ln effective distance	-0.505***	-0.451***	-0.388***	-0.258**	-0.364***
	(0.107)	(0.116)	(0.120)	(0.107)	(0.131)
ln Eucl. distance	-0.966***	-0.999***	-0.846***	-0.593***	-0.794***
	(0.075)	(0.082)	(0.125)	(0.064)	(0.096)
Intra-national ownership	1.287***	1.172***	1.157***	0.619***	1.667***
	(0.107)	(0.120)	(0.122)	(0.104)	(0.148)
Joint duration under Roman rule(centuries)		0.486***	0.485***	0.757***	0.179
		(0.171)	(0.172)	(0.150)	(0.222)
ln network distance			-0.230*		
			(0.138)		
Geography controls	No	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes
Observations	697,731	697,731	697,731	422,505	585,013
Estimator	PPML	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of firms in a cell i that are at least 50% (part) owned by firms located in grid j. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-national ownership' is a dummy variable that captures whether two grid cells lie within the same country. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. 'network distance' measures the length in kilometres of the distance-wise shortest path between grid cell centroids within the Roman transport network. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

D Business cycle co-movement

To investigate if the degree of business-cycle integration is influenced by connectivity within the Roman transport network, we draw on night-time luminosity data from the Defense Meteorological Satellite Program-Optical Line Scanner (DMSP-OLS) sensor. This data is available for the years 1992–2013 at a spatial resolution of 1×1 kilometres. Based on this information, we first determine overall night-time light intensity for each grid cell and year by summing up the light intensity indices of the individual 1×1 km pixels that fall into a given 0.5×0.5 degree grid cell. We then compute the annual growth rates between 1992 and 2013 for each grid cell. In a final step, we create two proxies for business cycle co-movement: The first is defined as the simple correlation coefficient in night-time light growth; the second as the correlation coefficient after the cyclical component has been removed using the Baxter-King filter. Table D.1 presents the estimates obtained from regressing these two proxies on effective distance. For both measures we find that greater connectivity within the Roman transport network increases business cycle synchronisation. The coefficients imply that correlation in night-time light growth decreases by 2–3 percentage points when effective distance increases by 1%.

The fact that effective distance affects both the intensity of interregional firm links and business cycle transmission accords with recent cross-country evidence on the close interrelationship between these two aspects of economic integration (Cravino and Levchenko, 2017).

Table D.1: Roman transport network and business cycle integration

Dependent Variable:	Nighttime Light Growth Correlation	
	(1)	(2)
ln effective distance	-0.019***	-0.032***
	(0.004)	(0.004)
ln Eucl. distance	-0.044***	-0.016***
	(0.002)	(0.002)
Intra-national ownership	-0.004*	-0.002
	(0.002)	(0.002)
Joint duration under Roman rule (centuries)	0.007**	0.019***
	(0.003)	(0.003)
Mean of dep. var.	0.657	0.761
SD of dep. var.	0.160	0.130
Geography controls	Yes	Yes
Destination FEs	Yes	Yes
Origin FEs	Yes	Yes
Observations	368,070	368,070
Baxter-King filter	no	yes
Estimator	OLS	OLS

Notes: This table reports estimates of Equation (1) using the OLS estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable in columns (1) and (2) is nighttime light growth correlation between grid cells i and j. This is an undirected measure, therefore only unique grid cell pairings are included in the regression. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-national ownership' is a dummy variable that captures whether two grid cells lie within the same country. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. Geography controls described in notes of Table 1. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

E Limes Germanicus

We support our argument that integration into the Roman Empire—and by implication its transport network—influences today's spatial firm ownership structure by documenting the existence of a stark discontinuity at the Limes Germanicus. As illustrated in Figure E.1 (a), this frontier line stretched across modern-day countries Germany and Austria and thereby separated the Roman Empire in the west from unsubdued Germanic tribes to the east.

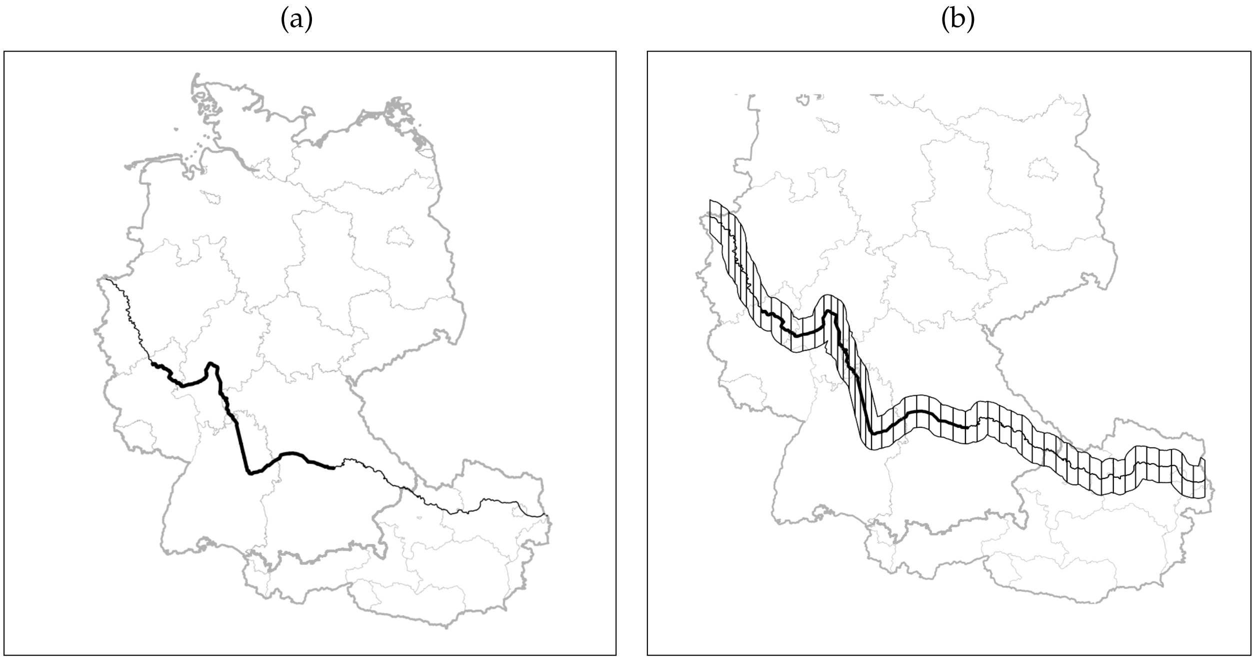

Figure E.1: The Limes Germanicus and Location of Grid Cells in the Border Sample
Panel (a) depicts the course of the Limes Germanicus within modern-day countries Germany and Austria. Sections of the Limes that do not follow the rivers Rhine or Danube are represented by bold lines. Light grey lines represent administrative-level borders (i.e., 'Bundesländer'). Panel (b) depicts the 100 regions created within the 50 kilometres buffer drawn around the Limes.

For our empirical test, we focus on the areas that lie within 25 km of either side of the former frontier.[91],[92] We then subdivide the area on either side of the border into 50 equally-sized zones, thus creating a total of 100 regions (see Figure E.1 (b)). On the basis of these regions, we construct measures of bilateral integration in analogy to our previous analysis (see Sections 3 and Appendix D).

In order to investigate whether the intensity of cross-regional firm ownership discontinuously changes at the Limes, we modify regression Eq. (1) by replacing effective distance with an indicator variable that takes the value one if regions are located on different sides of the former frontier. With this change, the estimating equation becomes:

$$\mathcal{X}_{ij} = \delta \, \text{Limes}_{ij} + T'_{ij}\gamma + \beta_i + \beta_j + \varepsilon_{ij}. \tag{E.1}$$

The dependent variable $\mathcal{X}_{ij}$ represents either the number of firms located in region j that are (part-)owned by entities located in region i or co-movement in night-time light growth. Whether

---

[91] That is, we construct a 50 km buffer around the Limes.

[92] Our results remain qualitatively unaltered if we restrict our analysis to areas that lie within 10 km of the Limes.

regions i and j are located on opposite sides of the Limes is captured by the dummy Limes$_{ij}$. The set of additional resistance terms (T) includes bilateral Euclidean distance as well as controls for administrative regions of level 1 ('Bundesländer'). Our regression model encompasses a full set of origin and destination fixed effects. Consequently, differences in time-invariant characteristics, such as geographical features or distance to the Limes do not generate identifying variation. Throughout, we two-way cluster standard errors (ε_{ij}) at the origin and destination grid-cell level.

The results of Table E.1 document that economic integration drops discontinuously at the Limes. The point estimate presented in column (1) implies that the number of cross-regional firm links decreases by $(\exp(-0.292) - 1) \times 100 = 25\%$ if two regions are located on separate sides of the Limes. The coefficient remains stable if we control for Bundesländer-pair fixed effects (column 2). The Limes effect on cross-regional ownership intensity is also reflected in columns (3)–(4), where we use night-time light co-movement as measure of economic integration.[93] In columns (5)–(8), we restrict our analysis to sections of the Limes that lie within Germany and do not coincide with the course of the rivers Rhine or Danube (see Wahl, 2017).[94] For these parts, the border effect is even more pronounced, strongly suggesting that the discontinuity is not generated by geographical borders (i.e., rivers) but man-made boundaries, i.e., the Limes.

Table E.1: Discontinuity at the Limes Germanicus

	All Sections Limes Germanicus				**Non-River Sections Limes Germanicus**			
Dependent Variable:	Number of Ownership Links (>25% Ownership)		Nighttime Light Growth Correlation (*std* 0.081)		Number of Ownership Links (>25% Ownership)		Nighttime Light Growth Correlation (*std* 0.051)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cross-Limes ownership	-0.292***	-0.223**	-0.002*	-0.002*	-0.343***	-0.328***	-0.004**	-0.004**
	(0.092)	(0.095)	(0.001)	(0.001)	(0.112)	(0.117)	(0.002)	(0.002)
ln Eucl. distance	-1.476***	-2.003***	-0.030***	-0.016***	-2.193***	-2.210***	-0.026***	-0.019***
	(0.114)	(0.117)	(0.003)	(0.002)	(0.109)	(0.114)	(0.002)	(0.002)
Intra-Bundesland ownership	0.619***		0.012**		0.272**		-0.004	
	(0.174)		(0.005)		(0.132)		(0.003)	
Admin 1 pair FEs	No	Yes	No	Yes	No	Yes	No	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Baxter-King filter	No	No	Yes	Yes	No	No	Yes	Yes
Observations	9,897	9,897	9,900	9,900	1,892	1,892	1,892	1,892
Estimator	PPML	PPML	OLS	OLS	PPML	PPML	OLS	OLS

Notes: This table reports estimates of Equation (1). Columns (1)–(2) and (5)–(6) estimated by PPML, Columns (3)–(4) and (7)–(8) estimated by OLS. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable in columns (1)–(2) is the count of firms in a cell i that are (part) owned by firms located in grid j. Dependent variable in columns (3)–(4) is nighttime light growth correlation between grid cells i and j. 'Cross-Limes ownership' is a dummy that takes the value one if two grid cells lie on opposite sides of the Limes. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-Bundesland ownership' is a dummy variable that captures whether two grid cells lie within the same Bundesland. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The results above document that the intensity of bilateral economic interaction discontinuously changes at the border of the former Roman Empire. While integration into the empire changed many economical and institutional aspect within regions, one important change was the connection to the transport network.

---

[93] We obtain qualitatively very similar results if we compute night-time light co-movement without applying the Baxter-King filter.

[94] This part of the Limes is represented as a thicker line in Figure E.1.

F Data construction for channels

Industry dissimilarity

We draw on Bureau van Dijk's Orbis database to construct a grid-cell-pair-level measure of industry dissimilarity. The procedure for constructing the measure is analogous to locating firms in patent-technology space developed in Jaffe (1986) in order to quantify R&D spillovers. In a first step we aggregate firms in a given grid cell to the three-digit NACE industry classification level, i.e., we create a vector of grid-cell-by-industry counts of firms. Next, we calculate a vector of the share of firms $F_i = (F_{i1}, F_{i2}, ..., F_{i344})$ in grid-cell i that are operating in industry x. In a final step, we produce a matrix of bilateral industry dissimilarity S, defined as the uncentred correlation of industry share vectors between any two grid-cells i and j, using the methodology established by Jaffe (1986):

$$S_{ij} = 1 - \frac{F_i F_j'}{(F_i F_i')^{\frac{1}{2}} (F_j F_j')^{\frac{1}{2}}}.$$

This measure lies between zero and one. It takes a value of zero for grids-cell pairs whose vectors of industry shares is identical and one for grid-cell pairs whose vectors of industry pairs is orthogonal, i.e., higher values reflect greater dissimilarity in the industry structure.[95] Interestingly, the measure has the advantage that it is not affected by the length of the F vectors, i.e., it will be robust to aggregation of classification levels such as moving from NACE 3 to NACE 2, whereas other distance measures might be sensitive to the distance between vector endpoints.

Preferences, values, and attitudes

We draw on the Global Preference Survey (GPS, Falk et al., 2018) and European Values Study (EVS wave 4, 2008)[96] to construct grid-cell-pair-level measures of preference and value (dis-)similarity. The GPS is an experimentally validated dataset—described in detail in Appendix A of Falk et al. (2018)—that collects 6 measures specifically designed to capture time preferences, risk preferences, positive and negative reciprocity, altruism, and trust. The survey covers all Western European countries except for Belgium and Luxembourg.

The EVS is a research survey program that covers all Western European countries and elicits information on ideas, beliefs, preferences, attitudes, values, and opinions of citizens in all Western European countries using a battery of questions. Following the EVS categorization, we group the questions into six topics, each covering a specific aspect of values and attitudes. The topics, along with the associated questions, can be found at `http://bit.do/evstopics`. For manageability reasons, we run a multiple correspondence analysis and compute the row coordinates of the first dimension within each topic and use the resulting values as the basis for our grid-cell-pair-level measures of similarity.

The procedure for constructing grid-cell-pair similarity measures from the individual-level information is the same for the GPS and the EVS surveys. In a first step, we purge all variables of country fixed effects. We then identify in which NUTS 2 region a respondent currently lives (GPS) or where she/he resided at age 14 (EVS). NUTS 2 regions are the most detailed

---

[95] For ease of interpretation, we have adapted the inverse Jaffe (1986) index to reflect dissimilarity. The original Jaffe (1986) index (O_{ij}), captures similarity and is given by: $O_{ij} = \frac{F_i F_j'}{(F_i F_i')^{\frac{1}{2}} (F_j F_j')^{\frac{1}{2}}}$.

[96] Data are available at `https://europeanvaluesstudy.eu/methodology-data-documentation/data-downloads/`.

spatial information available in the surveys. In a third step, we compute the average values of the preference and value measures for each NUTS region. These values are then assigned to the grid cells. If a grid cell falls entirely within one single NUTS region, it is simply assigned the NUTS 2 level average of the preference or value measure. If a grid cell overlaps multiple NUTS regions, we determine the share of total grid cell population that lives within each of the intersecting NUTS region and compute the population weighted averages of the respective preference and value measures.[97] In the final step, we compute the grid-cell-pair-level distance indices as the absolute difference between two grid cells in the respective preference, value or attitude measure.

Optimal Transport Routes Over Time

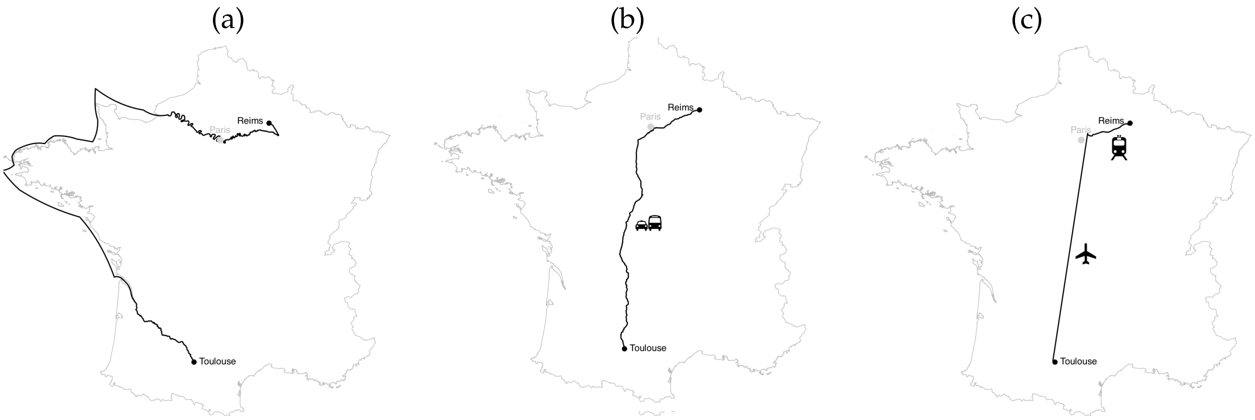

Figure F.1: Optimal Transport Routes Over Time
Panel (a) depicts the least-cost path between Toulouse and Reims within the Roman transport network; panel (b) shows time-minimising route using today's road network (Google Maps); panel (c) shows time-minimising path within today's passenger transport network (`www.rome2rio.com`).

---

[97] Formally, the population weighted measure M_i for a given grid cell i is defined as:

$$M_i = \sum_{n \in N_i} p_n m_n.$$

The proportion of total grid cell population living in NUTS 2 region n is represented by p_n, and m_n captures the NUTS-level average of a given preference or value measure.

Table F.1: Individual preference and value aspects: Accounting for potential channels

Dependent Variable:	Number of Ownership Links (>25% Ownership)								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ln effective distance	-0.526***	-0.372***	-0.338***	-0.261**	-0.523***	-0.421***	-0.371***	-0.340***	-0.153
	(0.111)	(0.111)	(0.109)	(0.111)	(0.111)	(0.101)	(0.101)	(0.099)	(0.099)
ln Driving distance (SD)		-0.890***		-0.612***					-0.431***
		(0.119)		(0.133)					(0.106)
ln Rome2Rio (SD)			-0.286***	-0.241***					-0.206***
			(0.026)	(0.029)					(0.025)
Industry dissimilarity (SD)					-0.149***				-0.133***
					(0.034)				(0.032)
Distance trust (SD)						-0.145***		-0.072	-0.063
						(0.045)		(0.044)	(0.039)
Distance altruism (SD)						-0.136***		-0.105***	-0.074**
						(0.034)		(0.032)	(0.030)
Distance negative reciprocity (SD)						-0.109***		-0.056*	-0.042
						(0.033)		(0.030)	(0.030)
Distance positive reciprocity (SD)						-0.175***		-0.148***	-0.133***
						(0.037)		(0.039)	(0.036)
Distance risk (SD)						-0.140***		-0.111**	-0.099**
						(0.050)		(0.049)	(0.045)
Distance patience (SD)						-0.066*		-0.047	-0.027
						(0.035)		(0.031)	(0.031)
Distance values & attitudes life (SD)							-0.149***	-0.140***	-0.138***
							(0.031)	(0.029)	(0.030)
Distance values & attitudes work (SD)							-0.156***	-0.126***	-0.109***
							(0.049)	(0.045)	(0.042)
Distance values & attitudes family (SD)							-0.029	0.000	0.003
							(0.032)	(0.030)	(0.031)
Distance values & attitudes politics (SD)							-0.058	-0.018	-0.015
							(0.044)	(0.043)	(0.039)
Distance values & attitudes religion (SD)							-0.125***	-0.075***	-0.075***
							(0.023)	(0.022)	(0.023)
Distance values & attitudes nationalism (SD)							-0.025	-0.001	0.013
							(0.038)	(0.037)	(0.039)
Intra-national ownership	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Joint duration under Roman rule	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geography controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Destination FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Origin FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ln Eucl. distance	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	671,512	671,512	671,512	671,512	671,512	671,512	671,512	671,512	671,512
Estimator	PPML	PPML	PPML	PPML	PPML	PPML	PPML	PPML	PPML

Notes: This table reports estimates of Equation (1) using the PPML estimator. Standard errors two-way clustered at the origin and destination grid cell level are reported in parentheses. Dependent variable is the count of firms in a cell i that are (part) owned by firms located in grid j. 'Effective distance' represents the cost associated with shipping goods along the least cost path given the Roman transport network and Roman-era-specific freight rates for each mode of transport. 'Eucl. distance' captures the length of the straight-line (as the crow flies) connection between grid cell centroids. 'Intra-national ownership' is a dummy variable that captures whether two grid cells lie within the same country. 'Joint duration under Roman rule' is the number of centuries two grid cells were jointly under Roman rule. Geography controls described in notes of Table 1. Preference and value distance measures described in Section 6. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

References

Archäologisches Landesmuseum Baden-Württemberg. 2006. *Imperium Romanum – Roms Provinzen an Neckar, Rhein und Donau: Begleitbuch zu Landesaustellung im Kunstgebäude Stuttgart vom 01.10.2005 - 08.01.2006.* Archäologisches Landesmuseum Baden-Württemberg.

Barjamovic, Gojko, Thomas Chaney, Kerem A. Coşar, and Ali Hortaçsu. forthcoming. "Trade, Merchants, and the Lost Cities of the Bronze Age." *The Quarterly Journal of Economics*.

Burriel Alberich, Josep, Albert Ribera i Lacomba, and María Serrano Marco. 2004. "A Fluvial Harbour of the Roman Period at Valentia (Hispania Tarraconensis)." In *Close Encounters: Sea and Riverborne Trade, Ports and Hinterlands, Ship Construction and Navigation in Antiquity, the Middle Ages and in Modern Time*, edited by Marinella Pasquinucci and Timm Weski, 129–138. Oxford University Press.

Campbell, Brian. 2012. *Rivers and the Power of Ancient Rome.* UNC Press Books.

Carreras Monfort, César, and Pau De Soto. 2008/2009*b*. "La red comunicaciones romana en Cataluña: actualizacion y metodologia." *ANAS. Aspectos de la red viaria hispano-romana* 21–22: 319–340.

Carreras Monfort, César, and Pau De Soto. 2009*a*. "La movilidad en época romana en Hispania: aplicaciones de análisis de redes (SIG) para el estudio diacrónico de las infraestructuras de transporte." *Habis* 40: 303–324.

Christakos, George, Ricardo A. Olea, Marc L. Serre, Lin-Lin Wang, and Hwa-Lung Yu. 2005. *Interdisciplinary Public Health Reasoning and Epidemic Modelling: The Case of Black Death.* Springer.

Cravino, Javier, and Andrei A. Levchenko. 2017. "Multinational Firms and International Business Cycle Transmission." *The Quarterly Journal of Economics* 132 (2): 921–962.

Cumberlidge, Jane. 2009. *Inland Waterways of Great Britain.* London: Imray.

Dannell, Geoffrey, and Allard W. Mees. 2015. "Getting Samian Ware to Britain: Routes and Transport Possibilities." *Journal of Roman Pottery Studies* 16: 77–92.

De Soto, Pau. 2013*a*. "El sistema de transportes del suroeste peninsular en época romana. Análisis de del funcionamiento de sus infraestructuras." *Actas del Congreso Internacional VI Encuentro de Arqueologí del Suroeste peninsular* 1551–1576.

De Soto, Pau. 2013*b*. "O irado Mar Atlântico: o naufragio Bético Augustano de Esposende (Norte de Portugal)." *O Irado Mar Atlantico. O Naufragio Betico Augustano de Esposende (Norte de Portugal),* edited by Rui Morais, Helena Granja and Angel Morillo, Chapter Los sistemas de transporte romanos y la configuración territorial en el noroeste peninsular, 179–210. Braga.

Dijkstra, Edsger W. 1959. "A Note on Two Problems in Connexion with Graphs." *Numerische Mathematik* 1 (1): 269–271.

Duncan-Jones, Richard. 1982. *Economy of the Roman Empire.* Cambridge University Press.

Eckoldt, Martin. 1983. "Schiffahrt auf kleinen Flüssen. Der Neckar und seine Nebenflüsse zur Römerzeit." *Deutsches Staatsarchiv* 6: 11–24.

Eckoldt, Martin. 1986. "Schiffahrt auf kleinen Flüssen. Nebenflüsse des Oberrheins und des unteren Mains im ersten Jahrtausend n. Chr." *Deutsches Staatsarchiv* 9: 59–88.

Falk, Armin, Anke Becker, Thomas Dohmen, Benjamin Enke, David Huffman, and Uwe Sunde. 2018. "Global Evidence on Economic Preferences." *The Quarterly Journal of Economics* 133 (4): 1645–1692.

Garcia, João C. 1982. "Navegabilidade e navegação no baixo Guadiana." Centro de estudos geográficos phdthesis, Lisbon.

García y Bellido, Antonio. 1944. "La navegación ibérica en la antigüedad, según los textos cisicos y la arqueologia." *Estudios Geográficos* 5 (16): 511–560.

Gattermayr, W., and D. Steck. 2006. "Innsbruck und das Hochwasser. Geschichte und Geschichten geschrieben vom Inn." Abt. Wasserwirtschaft beim Amt der Tiroler Landesregierung.

Hijmans, Robert J., Susan E. Cameron, Juan L. Parra, Peter G. Jones, and Andy Jarvis. 2005. "Very High Resolution Interpolated Climate Surfaces for Global Land Areas." *International Journal of Climatology* 25 (15): 1965–1978.

Hopkins, Keith. 1983. "Models, Ships and Staples." In *Trade and Famine in Classical Antiquity, Proceedings of the Cambridge Philological Society*, edited by P. D. A. Garnsey and C. R. Whittaker, 84–109. Cambridge: Philological Society Cambridge.

Jaffe, Adam. 1986. "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value." *American Economic Review* 76 (5): 984–1001.

Langmuir, Eric. 2003. *Mountaincraft and Leadership.* 3 edition. Manchester & Aviemore: British Mountaineering Council.

Latour, Louis. 2006. "Les fouilles gallo-romaines d'Auterive (Haute-Garonne), étude des couches les plus récentes." In *Mémoires de la Société Archéologique du Midi de La France*, 41–71.

Moret, Pierre. 2015. "Strabon et les fleuves gaulois." In *Les Gaulois au fil de leau. Actes du 37e Colloque international de lAFEAF (Montpellier, 8-11 mai 2013)*, edited by Fabienne Olmer and Rejane Roure, 217–234. ausonius.

Munoz, Alicia Fornell. 1997. "La navegabilidad en el curso alto del Guadalquivir en época romana." *Florentia Iliberritana* 8: 125–147.

Özak, Ömer. 2010. "The Voyage of Homo-economicus: Some Economic Measures of Distance." Department of Economics, Brown University mimeo.

Özak, Ömer. 2018. "Distance to the Pre-industrial Technological Frontier and Economic Development." *Journal of Economic Growth* 23 (2): 175–221.

Parodi Álvarez, Manuel J. 2012. "La navegación interior ibérica según Pomponio Mela: una visión de la Hispania Romana desde el Fretum-Gaditanum: ríos atlánticos peninsulares. Espacio y Tiempo." *Revista de Ciencias Humanas* 26: 137–156.

Pasquini, Béline, and Christophe Petit. 2016. "Le portage entre la Saône et la Moselle dans l'Antiquité (Ier-IVe siècles)." *Environnement et sociétés* 142: 27–32.

Scheidel, Walter. 2013. "Explaining the Maritime Freight Charges in Diocletian's Prices Edict." *Journal of Roman Archaeology* 26: 464–468.

Scheidel, Walter. 2014. "The Shape of the Roman World: Modelling Imperial Connectivity." *Journal of Roman Archaeology* 27: 7–32.

Wahl, Fabian. 2017. "Does European Development Have Roman Roots? Evidence from the German Limes." *Journal of Economic Growth* 22 (3): 313–349.

Wightman, Edith Mary. 1985. *Gallia Belgica.* University of California Press.

Williams, Nicola, and Virginie Boone. 2002. *The Loire.* Melbourne, Paris: Lonely Planet.