# The Diffusion of Epichoric Scripts and Coinage in the Ancient Hellenic Poleis [1] [2]

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Version April 4, 2022

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[1]The paper follows the convention in the classics literature and adopts Greek spelling, so that poleis is plural for polis.

[2]Earlier versions of this paper were presented at the Urban Economics Association meetings, CRETE 2021, Clark University, and the 2021 NBER Summer Institute – Urban Economics. Thanks go to Xu Dong, Teddy Glaeser, Gengbin Piao, Nicholas Reynolds, and Zach Sowerby for their help with the data, to Jack Kroll for exceptionally useful and constructive comments, but also to Panle Jia Barwick, Marcelo Bianconi. Giorgos Bourogiannis, Alain Bresson, John Brown, Alessandra Casella, Yannis Evrigenis, Michael Kosmopoulos, Ch. E. Maravelias, Eoin McGuirk, Dimitri Nakassis, Eleftheria Pappa, Robert Pitt, Albert Saiz, Enrico Spolaore, Adam Storeygard, Roger Woodard, and Junfu Zhang for useful suggestions, and to Josh Ober and Peter Van Alfen for data and many related suggestions and comments. We are grateful to Christopher Barnett, Uku-Kaspar Uustalu, Carolyn Talmadge and the other members of the Tufts Data Lab team for the construction of the data set for sailing times across the coastal segments of the Mediterranean and the Black Seas. We are also grateful to Sotiris Kampanelis and his coauthors for lending us their data on Phoenician sites. Comments received during presentations at CRETE 2021 and NBER SI 2021 by Marios Angeletos, Ed Glaeser, Matt Kahn, Theodore Papageorgiou, Giacomo Ponzetto, and Albert Saiz are gratefully acknowledged. Thanks also go to Stelios Michalopoulos, whose contribution to the research leading to a companion piece, Chen, Ioannides and Rauch (2021), titled "Asymmetric Trading Costs and Ancient Greek Cities" (currently in progress), was an important part early in this research effort. The usual caveats apply.

# The Diffusion of Epichoric Scripts and Coinage in the Ancient Hellenic Poleis

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**Abstract**

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The paper seeks to throw light at two discrete phenomena that were deemed as decisive for the development of the ancient Hellenic world and for urbanization in that part of the world via the emergence of sovereign urban entities, the Greek poleis. Although distinct, they are two conceptually and statistically interdependent aspects of total factor productivity. One is the *emergence of the ancient Hellenic (Greek) alphabet*, which we investigate via the diffusion of its antecedents, the *epichoric*, that is, its local ancient polis- and region-specific Hellenic scripts. It tackles, via formal economics tools, a phenomenon shrouded in mystery, namely how the Greek alphabet developed by tracking dates and locations where the various epichoric scripts diffused across the poleis of the ancient Hellenic world. The second is issue of *coinage* by Hellenic poleis, itself a path-breaking innovation, which allegedly started from ancient Lydia before it propagated in the Hellenic world and is matched only by the later development of coinage in China and India. Both these phenomena are motivated by means of simple theoretical models and are handled econometrically by means of similar econometric techniques, such as survival and other discrete but also linear regression methods, such as quasi-panel models of the spatial diffusion, while employing similar explanatory variables that allow for exploring their interdependence.

The underlying models of diffusion are modeled by means of novel applications of network tools, implemented on the system of poleis being defined as a weighted directed network. It is the asymmetry of maritime travelling and shipping costs that is responsible for directed weights. Network-based measures of centrality are also employed, in particular right and left eigenvector centrality (including Kleinberg's concepts of authority and hub centrality), in order to control for proximity in the aggregate sense.

**Keywords**: Hellenic scripts and alphabets, Phoenician script, diffusion of innovations, transportation networks, network centrality, ancient Hellenic poleis, system of cities, trade, economic geography, coinage issue, Delian league. Koinon.

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## 1 Introduction

The humanities literature is undecided to this day as to the precise geographical origin and date of the emergence of the Greek alphabet. It is widely accepted that it originated in the West Semitic script, and thus became known in the classical Hellenic world as $\Phi o\iota\nu\iota\kappa\acute{\eta}\iota\alpha$ $\Gamma\rho\acute{\alpha}\mu\mu\alpha\tau\alpha$ [*Phoenician Letters*]. According to Herodotus, the great historian of the Persian wars, 5.58:

> *"These Phoenicians who came with Cadmus* [ the mythological founder of Thebes] *and of whom the Gephyraeans were a part brought with them to Hellas, among many other kinds of learning, the alphabet, which had been unknown before this, I think, to the Greeks. As time went on the sound and the form of the letters were changed. [2] At this time the Greeks who were settled around them were for the most part Ionians, and after being taught the letters by the Phoenicians, they used them with a few changes of form. In so doing, they gave to these characters the name of Phoenician, as was quite fair seeing that the Phoenicians had brought them into Greece.1 [3] The Ionians have also from ancient times called sheets of papyrus skins, since they formerly used the skins of sheep and goats due to the lack of papyrus. Even to this day there are many foreigners who write on such skins."*

Modern scholarship recognizes that it was probably Greek speaking users of the new script who developed what came to be known as the Greek alphabet.[3] They did so by adopting Phoenician consonants whose phonetic values did not exist in the Greek language and by assigning Greek vowel values to those leftover consonant symbols. As Woodard puts it, those writers (perhaps even scribes) "thus created the first alphabetic writing system to represent systematically both consonants and vowel sounds" [Woodard (1997), p. 135-136, and fn. 7; Jeffery and Johnson (1990)].[4]

Whereas it is hard to argue with Herodotus, an eyewitness (of the particular inscription, at least according to his claim), the present paper is exploring the fair amount of scholarly

[3]As Ch. E. Maravelias prompts me, the title should refer to Alphabets, rather than Scripts, but we will defer to Anne Jeffery, whose major findings we are relying on, for consistency.

[4]The Phoenician alphabet has 22 letters and is syllabic, with each letter standing for a consonant and an unspecified vowel, which were not written. The scribes who most likely developed the Greek alphabet added letters, both to denote certain sounds, like $\Phi, X, \Psi$ and assigned vowel values to redundant (from the perspective of the Greek language) Phoenician letters. The Phoenician names of the letters, which are not known but scholars refer to them by their respective Hebrew ones, probably denoted initial consonants of words. Those names were largely adopted by the Greek alphabet. Characteristically, they are treated as foreign words in the Greek language, as indicated by the fact that they are not declined, even the ones that are associated with Greek words, like omikron and omega. The shapes of the letters, their order, and their names are very similar.

and epigraphic evidence on the diffusion of the epichoric, that is local Hellenic scripts. It is premised on the notion, succinctly put by Jeffery and Johnston (1990), p. 6, among their many arguments, "that the Greek alphabet must have had its birth either in a part of the Greek area where the people whom they [the Greeks] called *Φοίνικες* were active, or in part of the North Semitic area where Greeks were active." In considering alternative sites where this might have happened, Jeffery and Johnston emphasize three points: one, the alphabet must have originated in a limited area and was not created independently at a number of different sites where Greeks and Phoenicians had interactions; two, such a site had to be an established bilingual settlement of Greeks and Phoenicians rather than a mere trading North-Semitic trading post, of which there were many; and three, the alphabet's birth place must have itself been on a well-frequented trading route and/or with good connections with some of main trading centers of the Hellenic era.[5]

As there exist many variants of the epichoric scripts, this paper argues that the key element responsible for the diffusion is the *idea* of the alphabet itself, the *tacit agreement* whereby a sequence made up of a consonant and a vowel, with letters denoting sounds and together denoting a syllable, which constituted a fundamental step in establishing a standardized writing for the Greek language. Thus, a small number, 24, of symbols, formed the Greek alphabet before it diffused into the Latin one in the form of the Euboean script via the Etruscans. What motivated the emergence of the alphabet itself, is less well understood. Furthermore, the various epichoric scripts are quite similar to one another, so that users of some could decipher writing in others. It is reasonable to assume that it was interaction of Greek speakers with Phoenicians arguably most likely in bilingual communities, that allowed the invention of the alphabet. What appears to still be subject of debate is exactly where and when this occurred, namely the development of the form of writing in what came to be known as the Greek alphabet in the ancient Hellenic world. The emergence of the Greek alphabet must have had profound influence on the cultural and economic development of the Hellenic world.

Two key contenders for motivating the origin of alphabetic writing are: the needs of

[5]See Bourogiannis (2018b) for a discussion of the scope of cultural as well as economic contacts between Greeks and Phoenicians in the Aegean during the Early Iron Age.

the literature vs. the needs of trade. They continue to be hotly debated. The principal arguments in favor of the former is that there exist early attestations of writing in the Greek alphabet in the form of literature and casual writing, such as inscriptions that may be interpreted even as graffiti [Powell (1991; 1993)]. This is quite a contrast with the evidence in *Linear B*, the earliest form of syllabic writing of the Greek language that preceded the Greek alphabet, which is entirely devoted to records of economic transactions, tax records, and interactions between rulers, palace authorities and craftsmen ("contractors", a point forcefully made by Nakassis (2013)), all in the absence of inscription and money [Schaps (2004)]. Therefore, the question could arise as to why the next form of Greek writing, which emerged out of the so-called Greek Dark Ages (of several hundred years), would not have been invented in order to record details of, and to facilitate, the conduct of economic life.

Even if the primary motivation was the accommodation and effective communication of the emerging Greek literature [Powell (1991); Powell (1993), an entertaining contribution], it would still have served as a general purpose technology, and its emergence in effect being a total factor productivity (TFP) shock [*c.f.* Ashraf and Galor (2011)] within those trade-oriented communities. Therefore, evidence on the timing of presence of a script in different locations may be critical in understanding economic development in archaic and preclassical Greece, in addition to understanding the pattern itself of the spatial evolution of Hellenic scripts as propagation of total factor productivity shocks.

The first known records of the Greek language are in the form of the Linear B tablets and/or fragments thereof [Nakassis (2013)]. They have been found in a small number of locations, with their locations (and numbers in parentheses) are as follows: Knossos (4228), Pylos (1004), Thebes (438), Mycenae (107), Tiryns (76), Chania (52), and much fewer at each of a number of other locations, including writing on objects other than clay tablets. In most of those cases, the tablets were not meant to be permanent.[6] They have been preserved accidentally due to fires that destroyed the structures where they were stored. Therefore, those finds are hardly random, sparsely distributed and arguably very unrepresentative. Moreover, the record suggests that Linear B writing was restricted to administrative records,

[6] https://damos.hf.uio.no/1

as no inscriptions have been found. The paucity of those data makes us ponder about how to further use them and therefore we have not yet merged them with the scripts data.[7]

Several scholars have argued that the Linear B writing system, a syllabary, might have indeed been used first to record economic life, but those records were on perishable materials such as papyrus,[8] wood, parchment and leaves [Waal (2020), p. 113] in the same way that the cuneiform script was mostly tied to ephemeral materials such as papyrus, wood, parchment and leaves. It was only at later stages, when the use of writing extended to other (private) domains, that it also came to be used on more durable materials- such as pottery and stone." This suggests that we should not adhere too closely to attested dates of adoption and allow for errors, which we actually do in the empirical analysis.

The humanities and linguistics literature dwells at length on the precise nature of the innovation that the invention of the Greek alphabet amounted to, especially because it has served not only as the "mother of all European alphabets," but also of several Asian alphabets, though through different routes of transmission. The Latin alphabet, in particular, originated from the alphabet of Chalkis, Eretria, and Kyme, known as the Euboean script, through their colonies in Italy, especially Cumae, from which the alphabet was transmitted to the Romans via the Etruscans. Numerous variations followed, such as its adaptation for the needs of some Slavic languages, whereas the Cyrillic scripts were deliberately developed from the Greek for the needs of other Slavic languages. Since the creation of *pinyin*, a writing system of romanization of Mandarin Chinese, its influence has been extended even further.

In anticipation of taking the issue to the data, we discuss in further detail the question of where exactly the Greek alphabet was invented, as summarized by Bourogiannis (2018a). Proximity, not to mention coexistence, of Phoenicians and Greeks is attested in many places in the Aegean and indeed all around the Mediterranean. Most notable is Cyprus, though several scholars doubt that that is where the Hellenic alphabet emerged from the Phoenician script, because of the evidence that its Greek-speaking population held onto their own

[7]We thank Teddy Glaeser for his help with the Linear B tablets data and Albert Saiz for urging that we pursue this point.

[8]Jeffery and Johnston (1989), p. 57, state by appealing to Herodotus [v. 58] that before papyrus became an accepted medium, the Ionic Greeks had been using leather for the same purpose.

Cypriot syllabary over several centuries for political reasons [*ibid.* p. 252]. Critical to our empirical investigation is that scholars agree on the basis of linguistic arguments that the similarities across the epichoric scripts are so strong that the invention must have happened just once. In other words, it is unlikely that the invention took place spontaneously in different places. Thereafter, it propagated to and was adopted (with some variations) by different poleis at times ranging from 1100 to 750 BCE. Generally, there is little (but still some) support for an earlier date.

Until about 10 years ago, there was general agreement that later dates were more likely. Then firmly dated new archaeological findings at Methone, a northern Greek site in the region of Pieria, mitigated in favor of the alphabet being firmly established by 733 BCE and with a strong link to Eretria [ *ibid.* p. 244]. Specifically, this finding strengthens the case for an Aegean origin due to findings of coexistence of Greek along with Phoenician (and Phrygian) letters at Methone, a colony of Eretria in Northern Greece [Papadopoulos (2016); Bourogiannis (2018a; 2018b)]. An even earlier date of 775 BCE for the use of the Greek alphabet (though not necessarily representing Greek text) is attested at a site called Gabii in ancient Latium, Italy, for which there exists strong evidence of links with Eretria due to Eretrians' presence in Pithikoussai, Naples, Italy, where evidence of Greek writing has also been found, though associated with a later date. Many sites around the Aegean are known to have hosted strong Phoenician presence, including in addition to Eretria, Kyme and Oropos (the Euboeans), such poleis as Athens, Delos, Thera, Rhodes and Crete. Scholars have discussed their potential as sites for the invention. However, the Euboeans seem to stand out for active and reciprocal contacts with the Eastern Mediterranean. An additional argument has been made that involves a Phrygian link. Linguistic arguments that involve vowels in early Greek and Phrygian, together with the Phoenician symbols from which they seem to have been derived, plus the testimony of Herodotus, argue that the place of the adoption and adaptation of the Phoenician script must have been where Greeks, Phoenicians but also Phrygians interacted. This, again, points to somewhere in the Aegean. In sum, while we allow for many possibilities, we do think it is somewhere in the Aegean where the Greek Alphabet was invented. The paper tests this conjecture. Last, on a matter of terminology, we note that we adhere to the term *scripts* in deference to Jeffery (1961), but what did diffuse in the ancient Hellenic world were variants of what is nowadays known as the *Greek alphabet.*

Issue of coinage by Hellenic city-states, which are referred to as poleis in this paper, is associated with similar conceptual issues. A *tacit agreement* is at the heart of standardizing coins and stamping them with logos reminiscent of poleis, their rulers, products or deities. Quantities of precious metals had been used in effect as commodity money, but the accumulation of hoards of precious metals were not perceived as money as such.[9] The spread of coinage began with coins made of electrum, a naturally occurring alloy of gold and silver that occurs naturally in the area of Mount Tmolos and could be panned out of Paktolos River in ancient Lydia (east of modern Izmir). Electrum coinage appeared "somewhere between 650 BCE and 550 BCE in Asia Minor, at the interface between the Greek and the Asian world" [Velde (2014)].[10] Because of the naturally occurring differences in the content of gold and silver, a certification process was necessary to make those coins able to travel and be negotiable as money. A common weight standard had to be adopted, and scholars associate it with Miletus [Hodos (2020), p. 70]. As Hodos puts it, "it was the idea of coinage, rather than the Lydian coin system itself, that traveled where coins were used for local and regional purposes" [*ibid.* p. 70]. From around 610 BCE on, coinage and standards, initially different but ultimately standardized, diffused throughout the system of Hellenic poleis. So, again a *tacit agreement* is also at the heart of the invention of coinage, indeed a revolutionary invention [Schaps (2004); (2006)], that is stamped with the authority of the polis that issued it.

As Bresson (2005) and Schaps (2004; 2006) also argue, coinage of precious metal was an innovation, over and above commodity money (skins, cattle, shells, pieces of metal, etc. ) because: it signaled authority of the state via its stamp, allowed exchange rates with all commodities, and thus served as unit of account, store of value and medium of exchange.

[9]The reasons coins were issued in the first place is also debated by the literature, but is not discussed here. In this connection, see Howgego (1990) and Bresson (2005).

[10]"It was continued and emulated throughout the Greek world (though not, at first, the Asian world), but with a substantial change: from [King] Croesus onward, coins were made of either gold or silver, as a rule practically pure" *ibid.*

These properties coincide with the modern definition of money. The invention of coinage facilitated transition[11] of the Hellenic poleis to market economies [Bresson (2005); Schaps (2004)], and it is exactly to a better understanding of this urbanization process that the present paper seeks to contribute.

The emergence of coinage in India and China appears to come later. Schaps (2004), p. 231-233, acknowledges the controversy and dates coinage in India to probably before the invasion by Alexander the Great in the late fourth century BCE, but not earlier than Lydia. The case of China is similar, and coinage with similar functions to that of Lydia appears first in the early fifth century BCE. The fact that the technologies involved were different, punch marked silver coins in the former, and elaborate bronze cast in the latter, makes it likely that they were independent inventions. As Schaps (2004) argues, the roughly contemporaneous Indian and Chinese societies were too sophisticated to have settled on clumsy imitations of the Lydian and Greek process. Coinage must have been independently invented there and curiously did not immediately spread to equally sophisticated societies elsewhere.[12]

The remainder of this paper first presents the basic facts in additional detail. Section 3 outlines a set of related models of inter-polis interactions that allow us to structure analyses of the adoption of a script and issue of coinage by Hellenic poleis. The models lead to specific predictions about the spatial pattern in script adoptions and coinage issuance. The latter is analyzed in the context of inter-polis equilibria under different trade and coinage issuance regimes, such as issuing own coinage vs. adopting a common coinage. These models accommodate inter-polis trading costs, which in turn allow novel concepts of trading network centrality. The full analytical details of the equilibrium models of trading poleis with coinage are given in Appendix A. Section 4 presents the data and the estimation results, starting with comparisons of the role of centrality in script adoption and coinage issue and of the statistical interdependence of those outcomes, and continuing with survival models for the

[11] "Around 600 BCE, the Greeks were in a phase of transition towards a market economy." [Bresson (2005)]

[12] As Schaps (2006) p. 32, puts it, "Whether they each invented it independently or whether it passed from one to the other, Lydia/Greece, India, and China all proved fertile ground for an institution that neither originated nor was quickly adopted in other civilizations no less advanced culturally and economically. In fact, there are some parallels in the development of the economies of Lydia, India, and China that may be significant for our understanding of their role."

times till adoption of a script and issue of coinage. Presentation of estimates obtained with pseudo-panel models of the spatial evolution of script adoption and coinage issue completes the discussion of empirical results. Section 5 concludes.

## 2 Facts

Woodard (1997), Ch. 6, argues that scribes literate in the Cypriot syllabary were responsible for the first Greek adaptation of the alphabet. Woodard's argument rests on investigations of the spelling principles of the Mycenaean and Cypriot syllabic scripts. The magnum opus in the topic is Jeffery (1961) and its second edition Jeffery and Johnston (1990).[13] We digitize data from Jeffery and Johnston (1990) on our own. However, since the appearance of Jeffery's published work, her archive of documents has been digitized and is available online at http://poinikastas.csad.ox.ac.uk/. We are making full use of this resource.[14]

Our database of scripts is composed of 151 scripts attested with individual poleis, and 23 regional scripts. While it is not clear if the script for each individual polis is used by their neighbors or other nearby poleis, the regional scripts were likely shared by poleis in the same historical region, especially as in most cases they are associated with the same dialect: poleis within a historical region choose to adopt the same script. However, Johnston (1998) in discussing the potential significance of script adoption for polis identity, *polisism*, argue that the evidence in favor of a link between script and dialect is not very persuasive, but perhaps epichoric scripts were more likely a ““slip of the pen” than being associated with polis identity. Johnston does grant nonetheless that “polisism, did have some effect in perpetuating the use of home-town lettering in the propagandistic situation afforded in these sanctuaries [Delphi and Olympia] ...” [*ibid.* p. 428].

We do not know exactly why some scripts are regional while others are not, but one

[13]We thank Robert Pitt for suggesting this crucial source.

[14]It lists by order of appearance all 1640 items in Jeffery (1961), with details as follows: *Local Scripts of Ancient Greece* reference (with hyperlink to image), name of local script, region found (classified by means of maps), subregion, archaeological context, object type, and date range. For example, for the first line, the entries are: link to image, Attica, Central Greece (CG), Attica, Athens, Oinochoe, c. 725. In principle, these items may be classified in further detail and we are in the process of exploring these resources.

potential explanation is that regions with more within-region communication can share a script more easily. In the absence of a direct measure of within-region communication, we compute the average travel cost between all poleis within each region. We find that the 22 regions that do not have a regional script have greater average within-region travel costs than the 23 regions that do have regional scripts: the mean of the average within-region travel cost for regions with regional scripts is about 68% of the respective mean for regions without regional scripts, evaluated in terms of our baseline distance measure; it is 76%, 77%, and 85% in terms of our alternative distance measures.

Waal (2020), p. 111, states "alternatively, one could see the regional diversity as the results of local developments, which must have taken place over a longer period of time." As Luraghi (2010) puts it, although the local alphabets were consciously created and associated with ethnic boundaries and dialects, the problem remains how this all happens so rapidly. For our purposes, if we believe that the local development takes a long time, then the distance from each polis to particular Phoenician sites as potential origins of the innovation might not be as important. However, distance could matter when it comes to trade and to the degree of cultural differences. A key question is what explains that some poleis did adapt the Phoenician script, and when they did so, while others did not. A trade-related motive could be one potential explanation, as it led to cultural mixing. One the one hand, trade increases wealth and state capacity, which might go hand-in-hand with script adoption; on the other hand, the greater prosperity brought by trade could generate additional demand for record keeping and therefore for script. Coinage was of course crucial for trade, too, but unlike the case of script, it does depend on access to sources of precious metal, and therefore a joint treatment is appropriate.

# 3 Modeling Approach

As the analysis that follows suggests, the timing of both script adoption and coinage issue involves the full battery of micro- and macro-geographic information that proxies for their value in trade. Adoption of scripts and coinage issues are both associated with inter-polis externalities, and our models should reflect that. We proceed next with the details on the models that help structure our empirical investigations. Section 3.1 introduces a model of poleis as sovereign trading polities, section 3.2 discusses script adoption conceptually and section 3.2.1 the spatial aspects of script adoption. Section 3.3 turns to coinage, starting with conceptual aspects associated with coinage issue, and section 3.4 discusses utility comparisons across the different sets of options for poleis. Section 3.5 discusses measures of centrality that are helpful in serving as proxies for aggregating geographic and productivity parameters. Full analytical details backing up coinage issue with a system of trading poleis are given in the Appendix.

## 3.1 Model of Poleis as Independent Sovereign Polities

The ancient Greek city-states, the Hellenic poleis, were independent entities with each its own political structure, hence the terms "political" and "politics," that provided a basic infrastructure in the form of a legal structure, a process of collective-decision making, and several other institutions that constitute key predecessors of modern ones [Castoriadis (1991)]. Here we model poleis as independent polities within an overlapping-generations model framework that are populated by a large number of identical agents each living two periods. In the first period of their lives they work either for private firms or for the government, receive their wages, and save them; in the second period they consume their savings. Money, that is, coinage, is the only asset in the economy. If it is available, it is supplied by the polis government in order to finance the provision of a public good via new issues of coinage. The public good may alternatively be financed by a tax/transfer system. Firms set prices to maximize profits within the monopolistic competition setting associated with Dixit-Stiglitz preferences; alternatively, firms price competitively within the setting of the Armington model. Consumers in each polis consume quantities of all of the available varieties of the private good in the entire system of poleis, via an appropriately defined composite good, so as to maximize utility. The polis government chooses the money supply in order to finance the quantity of the public good that maximizes the discounted welfare of polis citizens at the steady state. The assumptions we make require that the public good be always provided.

They also make inter-polis trade beneficial. From a modeling perspective, accounting for a polis-specific public good is particularly important. The Greek poleis devoted substantial resources to public buildings, which vastly overshadowed private homes.[15]

The model that follows combines the static model of trade with shipping costs of Chen, Ioannides, and Rauch *et al.* (2021), itself a simplification of Allen and Donaldson (2018) but closely related to Allen and Arkolakis (2016), with a model with money, understood as coinage issue, that takes off from Casella (1992) (whose model assumes fiat money).

Trade presumes information: there is ample historical evidence of geography awareness of the extent of trade [Ioannides (2019)]. The spatial extent of ancient colonization also testifies to geographical awareness [Chronopoulos *et al.* (2021)]. We assume that each polis produces a differentiated good and employ the Armington assumption that goods are differentiated by origin, so that as many goods are traded as the number of poleis. Labor, supplied inelastically in quantity $S_i$, as in the standard international trade case, is the only factor of production in each polis $i$.[16] Each polis-specific good is produced with constant returns to scale according to the following production function

$$Q_i = A_i S_i, i = 1, \ldots, J, \tag{1}$$

where $J$ denotes the number of poleis, and $A_i$ TFP that may be specified in more detail as a function of geographical features, crop suitability, etc. for which it serves as a proxy.

Individuals work when they are young, receive their nominal wage $w_i$ and save it in the form of coinage. They spend their money holdings on differentiated consumption goods in the second period of their lives. They have identical CES preferences over the quantities of the $J$ differentiated consumption goods available in the economy, defined in terms of their

[15] Pounds (1969) states: "The city was judged by its public buildings. [Ancient author and traveler] Pausanias wrote 'if city it [Panopeus in Focis] may be called that has no government offices, no gymnasium, no theatre, no market-place, no water conducted to a fountain, and where the people live in hovels, just like highland shanties, perched on the edge of a ravine.' "

[16] Labor may be mobile, as in the so-called economic geography case, which we briefly discuss further in Appendix A; see Chen *et al.* (2021) for more detail.

CES aggregate,

$$H_i := \left( \sum_{j=1}^{J} c_{ji}^{\theta} \right)^{1/\theta}, \ 0 < \theta < 1, \tag{2}$$

and of the quantity of a public good $\Gamma_i$. The individual lifetime utility function is expressed as:

$$U_i = (1-g) \ln H_i + g \ln \Gamma_i, \quad i = 1, \dots J, \ 0 < g < 1. \tag{3}$$

To the subutility involving $\ln H_i$, (2), there corresponds an indirect subutility $\ln \left( \frac{Y_i}{P_i} \right)$, where $Y_i$ denotes nominal spending on the differentiated goods and $P_i$ the corresponding Dixit-Stiglitz ideal price index,

$$P_i := \left[ \sum_k \left( \tau_{ki} \frac{w_k}{A_k} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}, \ \sigma > 1, \tag{4}$$

where $\sigma := (1-\theta)^{-1}$, is the elasticity of substitution across intermediate varieties, $w_i$ is the equilibrium nominal wage, $\tau_{ij} > 1$ denotes shipping costs from $i$ to $j$, that is, the units of the good $i$ that must be shipped from origin site $i$ for one unit to arrive at a destination site $j$. It is proxied by the sum of imputed overland travel costs plus sailing times. Due to wind patterns, the sailing times components of these costs are asymmetric and therefore so are total shipping costs: $\tau_{ij} \neq \tau_{ji}$.

Let the total indirect utility function associated with (3) be denoted by $V_i$. Regarding its determinants, we note the following. It is a function of $Y_i$ and also of the trade regime, which also affects the mode of financing of the public good $\Gamma_i$. In one extreme, the case of autarky, it depends on the characteristics of site $i$ only. In the other extreme, the case of coinage union, as the Appendix details, it depends on the characteristics of all associated poleis and the entire structure of trade costs, as indicated by the definition of the price index $P_i$ above. As the Appendix details, the assumption of coinage union simplifies all associated endogenous quantities by rendering them independent of all wage rates but still dependent on all productivities and trading costs.

We note that with CES preferences and a fixed number of goods, as is the case of the Armington assumption with goods being differentiated by origin, the optimum value of the consumption subutility does not depend on polis size. However, it would do so in the case of the Dixit-Stiglitz model with CES preferences, monopolistic competition and endogenous number of goods. Regardless of how the public good is financed, its quantity does depend on polis size, and thereby a dependence of polis welfare on polis size is introduced.

## 3.2 Adoption of Scripts

A polis having a script in common with its neighbors and trading partners confers numerous advantages, principally among them ease of communication. While we are accustomed to evidence on such media as stone and objects made of clay, writing seems to have been present on numerous other objects, including coins, decorative objects and tools. The variety of objects mentioned in the *Local Scripts of Ancient Greece* database from *Poinikastas* is telling. In addition, most likely non-permanent media were used, such as hides and papyrus, just as we even today use all kinds of non-durable media. Indeed, the Greek word for book, *biblion* ($\beta\iota\beta\lambda\acute{\iota}o\nu$), derives from the name of Byblos, modern Jbeil, one of the most ancient cities that have been inhabited continuously since at least 7000 BCE.[17]

Modern scholarship on alphabets recognizes them as "not a script for performance, nor a faithful recording of speech. The legibility of alphabets, like other scripts, relies not on their phonetic accuracy relative to a given language, but on the agreements made between their users across space and time" [Frampton (2017)].[18] In Pliny the Elder's own words, *consensus tacitus* was involved in the adoption of the alphabet: "There was at the very earliest period a tacit consent among all nations to adopt the letters now used by the Ionians.[19]"[20] Although different poleis are attested adopting different versions of Hellenic scripts, so-called epichoric,

[17]It lies on the coast of Lebanon from where trade with Egypt, the origin of papyrus, a common raw material for writing in antiquity, was known to have taken place.

[18]Pliny the Elder calls writing one of civilization's greatest "tacit agreements" (along with beard-trimming and time-keeping). More recently, in his wonderful romp through the history of the English alphabet, Michael Rosen calls the rules of writing "more like treaties between consenting groups" [Frampton (2017)]. This is consistent with understanding the role of images, including those of coins, too, as informational vehicles in human cultural evolution [Pavlek (2021)].

[19]Ionians refers to Greek speakers residing on the Aegean coast of Asia Minor.

[20]http://www.perseus.tufts.edu/hopper/text?doc=Perseus:text:1999.02.0137:book=7:chapter=58. See *The Natural History. Pliny the Elder.* John Bostock, M.D., F.R.S. H.T. Riley, Esq., B.A. London. Taylor and Francis, Red Lion Court, Fleet Street. 1855

that is local, alphabets, the element in those adoptions that we stress is the element of *tacit agreement* over their use of an alphabet to record the spoken language.

Alphabets were a great departure from the Linear B or the Cypriot syllabary, that preceded them. The various epichoric scripts differed in many ways. To give examples, they differed in the use of the consonant symbols $X, \Phi, \Psi$, in the use of the innovative long vowel letters $\Omega$, and $H$; and many others, and in many details of the individual shapes of each letter. The now standard 24-letter Greek alphabet was originally the regional variant of the Ionian cities in Asia Minor. Yet the classics scholarship maintains that they were mutually intelligible. In fact, it has been said that ancient Greek as a language was defined in terms of the epichoric scripts as it originally lacked an universally acceptable alphabet. By the time Athens officially adopted the Ionian script in 403-402 BCE with Eucleides as archon [D'Angour (1999)], it became the standard in most of the rest of the Greek world by the middle of the 4th century BCE. Our coding of adoption dates adheres to this event.

### 3.2.1 Modeling Adoption of Scripts

We next model adoption of a tacit agreement at a spatial detail as follows. For analytical convenience, let $S_i = 1, -1$ denote that polis $i$ adopts, does not adopt a script. Two neighboring poleis benefit in utility amounts $(a, a)$ by both adopting a script. If polis $i$ adopts a script, $\text{Script}_i = 1$, and a neighboring polis $\nu(i) := \{i+1, i-1\}$ , does not, $\text{Script}_{\nu(i)} = -1$, polis $i$ and polis $i+1$, or $i-1$ benefit respectively by $(b, c)$, and vice versa, that is the setting is symmetric. If neither a polis nor its neighbors adopt script, $\text{Script}_i = -1, \text{Script}_{\nu(i)} = -1$, then the respective poleis benefit by amounts $(d, d)$. Assuming $a > d$ expresses the advantages of having a script, and $a > b > c > d$ expresses the superiority for two neighboring poleis of both adopting a script over only one of them having a script rather than no script.

In standard game-theoretic notation, the matrix of incremental payoffs is:

$$\begin{array}{r} \\ \text{Script}_{\nu(i)} = 1 \\ \text{Script}_{\nu(i)} = -1 \end{array} \begin{array}{c} \begin{array}{cc} \text{Script}_i = 1 & \text{Script}_i = -1 \end{array} \\ \left( \begin{array}{cc} (a, a) & (b, c) \\ (c, b) & (d, d) \end{array} \right) \end{array}. \tag{5}$$

In view of the problem at hand, we could without loss of generality assume that $b = c$, which imposes a certain symmetry. Script adoption is modeled as a game between neighboring poleis, where random factors are expressed via extreme value shocks so that the setting becomes that of a spatial logit model. That is, the payoff is expressed as a function of adoption strategies by poleis $i, j$, given by $(\text{Script}_i, \text{Script}_j)$. Konno and Ioannides (2019) provide an *exact* solution to the respective spatial logit model.[21]

We express that two neighboring poleis that interact would benefit from sharing a means of communication by adjoining a single parameter to the trade-related component of the utility function. Each polis $i$ is described by utility function (3). Let $i = A, B$ denote two interacting poleis. The matrix of payoffs instead of (5) now is:

$$\begin{array}{r} \\ \text{Script}_{\nu(i)} = 1 \\ \text{Script}_{\nu(i)} = -1 \end{array} \begin{array}{c} \begin{array}{cc} \text{Script}_i = 1 & \text{Script}_i = -1 \end{array} \\ \left( \begin{array}{cc} (V_i + a + \varepsilon_{aa}, V_{\nu(i)} + a + \varepsilon_{aa}) & (V_i + b + \varepsilon_{bb}, V_{\nu(i)} + b + \varepsilon_{bb}) \\ (V_i + b + \varepsilon_{bb}, V_{\nu(i)} + b + \varepsilon_{bb}) & (V_i + d + \varepsilon_{dd}, V_{\nu(i)} + d + \varepsilon_{dd}) \end{array} \right) \end{array}, \tag{6}$$

where we retain the assumption $a > b = c > d$, the $\varepsilon_{jj}$'s are random shocks, and the $V_j$'s denote indirect utility functions corresponding to utilities associated with different trade regimes. The additive random shocks are assumed to be independent and identically distributed across choices and obey the extreme-value distribution of type II. These assumptions yield spatial logit probabilities in closed form [Konno and Ioannides (2019)]. Once the script adoption decision has been made, then the indirect utility functions associated with the resulting regimes apply but the additive separability with respect to the communication

[21] In order to employ best the machinery of spatial social interactions as a spatial logit model we need to work equivalently by transforming the matrix of payoffs (5); see Konno and Ioannides (2019).

component is unaffected by it. However, it is simplest to restrict attention to two extreme cases of trade regimes: autarky and coinage union. The Appendix considers alternative trade and coinage regimes across the system of poleis and provides details on the coinage union.

Specifically, let poleis ("agents ") be arranged around a circle. However, as it is shown in *ibid.*, that particular topology is not crucial for results in the limit with many decision making units; they also apply for agents arranged on a line. Konno and Ioannides (2019) explore the full spatial logit model by means of tools of statistical mechanics. By working with the full set of configurations of cardinality $2^N$, they characterize the steady state probabilities of strategies,[22] the correlation function for strategies as function of the graph distance among poleis, and the expected utility of the process. However, it is easier to work with the probability at the steady state for any polis $i$ to adopt a script, $p_{\text{Script}_i=1}$, which is given in closed-form by

$$p_{\text{Script}_i=1} = \frac{\exp\left(\beta \frac{\Delta_1}{4}\right) \sinh(\beta \frac{\Delta_2}{4})}{2\sqrt{\exp\left(\beta \frac{\Delta_1}{2}\right) \cosh^2(\beta \frac{\Delta_2}{4}) - 2\sinh(\beta \frac{\Delta_1}{2})}} + \frac{1}{2}, \tag{7}$$

in the limit as the number of poleis $N \to \infty$, where $\beta$ is the dispersion parameter of the underlying extreme-value shock distribution, and $\Delta_1 := a - b - c + d; \Delta_2 := a + b - c - d$. There are in effect three parameters involved in (7) $(\beta, \Delta_1, \Delta_2)$. Because of symmetry, this expression applies for any polis in the system.[23]

Two special cases are noteworthy. One, if the random shock is very large, in the limit being represented by the variance of the shocks tending to infinity, $\beta \to 0$, then randomness does not matter and the deterministic outcome of equal probabilities prevails. In that case, (7) yields $p_{\text{Script}_i=1} = \frac{1}{2}$ (and (8), fn.9, yields $E[S] = 0$). Two, if the random shock is very

[22]The model may be cast in a dynamic setting, a case that is discussed in *ibid.,* section 5.

[23]An alternative approach, known as the *mean-field approach*, which conveys similar qualitative implications of the model, is to seek instead a solution for the expected outcomes. The expected outcomes, defined as $E[\text{Script}_i] = 1 \times p_{\text{Script}_i=1} + (-1) \times p_{\text{Script}_i=-1}$, are implicitly given by the roots of:

$$E[\text{Script}_i] = \tanh\left[\beta\left(\frac{\Delta_1}{2} E[\text{Script}_i] + \frac{\Delta_2}{4}\right)\right]. \tag{8}$$

Equation (8) admits, in general, two stable roots and one unstable one [Ioannides (2013), Ch. 2]. The stable ones correspond to either all adopting or not adopting, where the unstable one corresponds to one adopting and the other not adopting.

small, thus unimportant, its variance is zero, represented by $\beta \to \infty$, then the choice is deterministic and depends only on the relative magnitudes of $a-b-c+d$ and $a+b-c-d$. This is confirmed by how parameters enter in equation (8). Therefore, empirical evidence of effects may be interpreted through this model. For example, $a-b-c+d = a-b-(c-d)$ denotes the relative advantage of $i$'s having a script and of $\nu(i)'$s not having a script.

The above exposition emphasizes the spatial detail and characterizes the exact solution of the spatial logit model, equation (7). In the general case of stochastic steady states, clusters of poleis adopt a script. However, the same model may motivate the dynamic evolution of adoptions. Theoretically, potential adopters may be prompted randomly by means of a "Poisson clock" device [Blume (1995)], given the state of adoption by neighboring poleis, rather than all at once. However it may be modeled, we may obtain a dynamic spatial diffusion model, with script adoption by a polis depending on the state of their neighbors in the preceding period. Adapting Konno and Ioannides, *op. cit.*, section 5.3, let $\mathbf{Script}_t$ denote the $J-$vector with entries $\text{Script}_{i,t},\ i=1,\ldots,J$. We may move to a dynamic analysis with social interactions in nonlinear settings by assuming that agents make decisions with knowledge of the actual state of their neighbors in the preceding period, given an *arbitrary* interaction topology $\mathcal{G}$. That is:

$$\mathbf{Script}_{i,t} = \mathbf{1}_i\left[2h + 2\mathcal{G}_t\mathbf{Script}_{t-1} + \varepsilon_i\right],\ \text{if } \mathbf{Script}_{i,t-1} = -1; = 1,\ \text{otherwise}, \qquad (9)$$

where $\mathcal{G}_t$, the matrix of interaction coefficients, subsumes the adjacency matrix of the interaction topology and adjusts for the number of neighbors, a $J \times J$ matrix, $h$ is a function of parameters, and $\varepsilon_i$ is defined as the difference of 2 independently and identically type II extreme-value distributed random variables, $\varepsilon_i = \epsilon_i(1) - \epsilon_i(-1)$, written as a column vector, $\varepsilon \equiv \epsilon(1) - \epsilon(-1)$, and $\mathbf{1}[\mathcal{R}_t]$ is an indicator function of the $J-$vector $\mathcal{R}_t$, with its $i$th element, $\mathbf{1}_i[\mathcal{R}_t]$, equal to 1, if the $i$th element of $\mathcal{R}_t$, $\mathcal{R}_{i,t} > 0$, or if $\text{Script}_{i,t-1} = 1$, and is equal to $-1$, otherwise. Equ. (9) represents a nonlinear dynamic autoregressive model for discrete endogenous variables corresponding to the static spatial model presented earlier in this section. The reaction functions, the entries in the r.h.s. of (9), are generally sigmoid in the lagged state. In section 4.5 below we adapt this formulation to linear regression settings where previous adopters influence subsequent adoptions but do not reevaluate their decisions. We account for the complexity of spatial detail by adapting equation (9) so as to allow for the full range of adoption models in the literature, including notably those in Young (2009).

A key prediction of the exact solution version of the spatial logit model (as well as of the nonlinear dynamic autoregressive model) is that the decisions of the different poleis attenuate spatially [*ibid.*, Proposition 2]. That is, intuitively, clusters of adjacent poleis emerge that either all have all adopted or none has adopted. It is this implication of the model that we take to the data while adapting it to our spatial setting, including geographic characteristics, local as well as distance, centrality, and trading cost related. Indeed, The map in Figure 1, a modernization by Voutiras (2007) of a map by Kirchhoff originally drawn in 1867, confirms such clustering.

## 3.3 Coinage

We characterize alternative trade regimes and associated modes of financing the provision of the public good starting with autarky. A polis in trade autarky may finance the provision of the public good by means of either taxes or coinage, which may circulate locally only. However the provision of the public good may be financed under autarky, it absorbs a share $g$ of the resources of each polis. In the absence of trade, only the locally produced good is used for local consumption and provision of the public good. The wage rate is $w_i = A_i p_i$, $H_i = (1-g)A_i S_i$, $\Gamma_i = g A_i S_i$, and the corresponding utility function[24] is given by:

$$V_{i,aut,no\ coinage} = \ln\left[(1-g)^{1-g} g^g\right] + (1-g)\ln A_i + g \ln S_i. \tag{10}$$

If a polis were to issue coinage and use it only locally, it would do so as to finance a real quantity equal to $gS_i$ at the monetary steady state. The value of the corresponding utility

[24] An alternative model with Dixit-Stiglitz preferences and endogenous number of consumption varieties via a monopolistically competitive market structure would lead to a similar expression for $V_{i,aut}$ except for the fact that the coefficient of $\ln S_i$ would also include the substitution parameter, and so would the associated constants.

function is given by

$$V_{i,aut,\,coinage} = \ln\left[(1-g)^{1-g} g^g\right] + (1-g)\ln A_i + g\ln S_i - g\ln \mu_i. \qquad (11)$$

Whereas the cost of coinage $\ln \mu_i$ enters the definition of $V_{i,aut,\,coinage}$, its benefits do not, as they have not been quantified and may also depend on $S_i$. In particular, $\mu_i$ may increasing in the distance or shipping costs from sites or other poleis near mines.

Using coinage outside a particular polis' economy presumes that it would be negotiable. Under interpolis equilibrium with each polis issuing its own coinage all product varieties would be traded. The imported quantities would be purchased with the coinage of the poleis where they are produced. Therefore, at interpolis equilibrium exchange rates would be established. Each polis faces a total money budget constraint: total money demanded by the young must equal total money supplied by the old plus newly created money. The quantity of the public good is equal to real money creation in each period. Because all goods are consumed in every polis, equilibrium utility in every polis depends on the sizes of all poleis.

Working with exchange rates and many trading entities is a standard problem in international economics but analytically complicated. As we are interested in merely motivating empirical investigations, we work with two extreme alternatives: autarky with or without coinage, and coinage union. For coinage issued by different poleis to be negotiable, or for common coinage to be adopted, the notion of a *tacit agreement* similar to the one underlying script adoption is also involved, thus making issuing coinage conceptually akin to script adoption. This is particularly important when we recognize, as we have discussed earlier, what an extraordinary innovation issuing coinage has also amounted to. There is, however, an important difference, namely that theory allows us to be analytically more precise about the determinants of issuing coinage or joining a coinage union.

A model of interpolis interdependence through trade with and without common coinage, which we have adapted from Casella (1992), is given in Appendix A. Allowing for common coinage issue introduces some important features as well as simplifications. With nominal wage rates being equalized within the coinage union, the monetary budget constraints of all poleis may be aggregated. This in turn implies that seignorage may be shared among the members of a coinage union. If different poleis that are members of a coinage union engage in uncoordinated coinage issue in a Nash equilibrium context, the resulting equilibrium might place some poleis at levels of welfare that might be inferior to that of autarky. This comparison is complicated by the fact that the cost of issuing coinage may depend on a polis' access to precious metal either via proximity to mines or via trade. Recognizing such outcomes implies constraints on the sharing of seignorage by the union or the coinage hegemon.

Therefore, whether or not a polis benefits by issuing its own coinage and operating in autarky versus participating in a coinage union depends upon the design of the coinage union.[25] This is particularly important to our setting. A smaller polis may avail itself of the alternative to revert to the Nash equilibrium with all poleis issuing their own coinage, and trading by means of their own coinage, or even going into autarky. Consequently, we show in the Appendix that equilibrium utility in every polis depends on the sizes of all poleis, in addition to the full set of parameters characterizing the entire system of poleis. The model in the Appendix extends Casella (1992) by introducing trading costs affecting interpolis trade, along the lines of Chen, Ioannides and Rauch *et al.* (2020), while allowing for coinage issue.

Specifically, from the definition of the indirect utility function (3) above (see also Appendix, equation (38)) in the case of interpolis trade with many poleis under the Armington assumption the semi-indirect utility from trade, which is easiest to express when the trading poleis are members of a coinage union, is given by:

$$V_{i,trade,\ union} := (1-g)\ln y_i + \frac{1-g}{\sigma-1}\ln\left[\sum_k \left(\frac{\tau_{ki}}{A_k}\right)^{1-\sigma}\right] + (1-g)\ln\left[\frac{\bar{S}-\sum_i \mu_i m_i}{\bar{S}}\right] + g\ln m_i - g\ln \mu_i, \tag{12}$$

[25] Casella (1992) shows that in a monetary union made up of two countries, there exists a minimum weight for the utility function of the smaller of two countries in the union such that for all countries with smaller sizes a larger relative weight in aggregate welfare will be required than its relative size, in order for such a country to be willing to join the monetary union, instead of having its own national currency. If this were not the case, the control exercised by the larger economy would result in a very unbalanced solution of the externality problem: the small economy would end up facing the costs of the coordination without reaping enough of the benefits.

where $y_i$, polis $i$ real income, and $m_i$, real coinage issue for polis $i$, are functions of all parameters, that is polis sizes, shipping costs, coinage costs, and productivities. The expressions for $y_i, m_i$ are given (in vector form) in the Appendix, equations (41) and (40). The allocation of seignorage to the supply of the public good in each polis depends on a polis $i$'s own coinage cost $\mu_i$, on the coinage costs $\{\mu_j, j \neq i\}$ of all poleis that are members of the coinage union, and all shipping costs and productivities as aggregated in the ideal price index (31). We could therefore derive a condition that suggests the existence of a threshold on shipping costs which would define a region of monetary dominance for a particular polis. Appendix, section 6.2, discusses such issues in the context of coinage unions, applied more generally to how advantageous access to mines of precious metals by a polis may be used strategically to either induce or discourage another polis with inferior access from issuing its own coinage.

The notion of a coinage union is not at all as farfetched as it might sound. Indeed, the literature on the *Athenian Coinage Decree*, a.k.a, *Coinage, Weights and Measures Decree,* circa 450 – 447 BCE, discusses that the members of the Delian League[26] were required to turn in their coinage to the Athenian mint in exchange for Athenian coinage, with the Athenian mint earning seignorage. It is thus appropriate as an operating hypothesis. As Kallet and Kroll (2020), but also Hodos (2020), emphasize, coinage (or for that matter "numismatic") policy may not be easily distinguished from general trade policy, which required harmonization of standards for weights and measures, as well. It is thus in this broader sense that choice of coinage is interwoven with choice of trade regimes. Furthermore, the tributes that the Delian League members were required to pay also contributed to the dominance of Athenian coinage along with Athenian hegemony more generally.

Indeed, Athens as the undisputed coinage hegemon of the classical era via the Delian League during much of the 5th century BCE was able to manipulate the conditions facing the poleis members of the League. The league was a coinage union, originally *de facto* and later on *de jure*, and enforced compliance by a variety of means, including use of military threats and the like.[27] Therefore, our employing information on Delian League membership

[26]See Kallet and Kroll (2020) and Hansen and Nielsen (2004), pp. 111–114. For a list of all Delian League members, see *ibid.*, Index 18, pp. 1356–1360.

[27]The numismatic history of ancient Hellas suggests that many poleis and even smaller ones were able to

allows us to test its impact on a polis' coinage issuance decision. As indicated earlier, Athens required member city states, which by then made up the Athenian Empire, to pay tributes [Nixon and Price 1990)] and to submit their coinage and have it reminted. In view of the evidence that the tribute quotas appear some times to be disproportionate to polis reputed economic resources, commentators have suggested that other considerations must have been at play, such as punitive intentions or attempts by Athens to be compensated for costs it incurred on besieging them [ Kallet and Kroll (2020), p. 68].

### 3.4 Predictions Regarding Coinage

As discussed above, under autarky, costly own coinage would be inferior to a system of taxes and transfers, were it not for the advantages that coinage confers in facilitating domestic as well as external trade. Unfortunately, the analytics of the case where poleis trade by means of their own coinage do not admit closed-form solutions. As we have already discussed, comparisons of coinage regimes is simplest between autarky and membership in a coinage union. A polis' availing itself of the advantages of coinage depends on access to supply of precious metals and trade, choosing the least costly alternative. So, in sum, a polis may exist in autarky with or without own coinage, may participate in interpolis trade, earn coinage from trade and thus issue its own coinage, or may become a member of a coinage union, whereby coinage issued by different poleis would have to conform to the common standards.

Even under conditions of trade autarky, it is reasonable to assume that coinage issued by polis $i$ in order to facilitate domestic commerce only does depend on polis size. Whether or not polis $i$ monetizes rests on the relative magnitudes of $V_{i,aut,nocoinage}$, and $V_{i,aut,coinage}$, defined in (10), respectively:

$$\text{Prob [polis } \ i \ coinage|autarky] = \text{Prob}[V_{i,aut,coinage} \geq V_{i,aut,no\ coinage}]. \tag{13}$$

This comparison depends on the size of polis $i$ relative to the cost of issuing its own coinage,

thrive on their coinage. A notable example is Aegina, a tiny island across the Saronic Gulf from Athens, whose "turtles" competed with the Athenian "owls", where the common ancient nicknames for the respective coinage are invoked.

$g[\ln S_i - \ln \mu_i]$, since TFP, $A_i$, is the same under autarky of either kind. However, it is reasonable to expect that the benefits from issuing coinage that are functions of size are functions of $A_i$.

If it pays for a polis to issue coinage, then a question arises about whether it would pay for it to do so and enter a coinage union with other poleis. Let us consider poleis $i$, and $j$, for which $\mu_i = 1$, and $\mu_j > 1$, which would place polis $i$ in an advantageous position to be a coinage hegemon. Whether or not polis $j$ would find it attractive to join such a union with $i$ depends on the comparison between $V^*_{j,trade,\, union}$, and $V_{j,aut,\, coinage}$, where $V^*_{j,trade,\, union}$ would denote a modification of (12) that accounts for sharing of seignorage. As we discussed earlier, such sharing must be sufficient to make it advantageous for $j$ to join a union with $i$. However, if $\mu_j$ is too large, because $j$ is too far from $i$ and $i$' proximity to mines, $i$ might consider it too costly to make it sufficiently attractive to $j$. However, since the optimal solutions for $(y_i, y_j)$ as functions of $(m_i, m_j)$ depend on all productivities and trading costs, holding constant $j$'s centrality (see below) and given membership to a coinage union with $i$, it is possible that the more distant is $j$ from $i$, a polis with known proximity to mines, the more likely would be for $j$ to issue coinage earlier. This suggests that, in principle, the effect of distance of $j$ from $i$ would be ambiguous.

So, in general, when coinage and trade are allowed, there are three possibilities. One, a sufficiently high coinage cost would keep a polis in autarky with no coinage; two, an intermediate value would allow it to issue its own coinage; and three, sufficiently low trading and coinage costs through the system of poleis that adopt a common coinage would induce it to participate in the common coinage. However, the latter is determined critically by geopolitical considerations and the prevalence of a coinage hegemon, as we have already discussed. In section 4.3.2 we adapt equation (9) to describe adoption of coinage.

## 3.5 Measures of Centrality

Appendix A obtains a solution for polis incomes as functions of polis sizes, $\mathbf{S}$, and of all parameters, under the assumption of monetary, that is, coinage union. The solution involves matrix $\mathbf{T}^*$, defined in (43), which may be used to obtain a proxy of the incomes of poleis that are proportional to the right eigenvector centrality of $\mathbf{T}^*$. Thus motivated, we develop three alternative concepts of centrality. One is simply *eigenvector centrality* based on the Perron-Frobenius right eigenvector of $\mathbf{T}^*$. In addition, We follow Kleinberg (1999) and introduce two others: *hub* and *authority centrality*, which are similar to network centrality in the sense of the `PageRank` algorithm.

Adapting Kleinberg's terminology, *authority* poleis are those which it is easier to ship *To*; *hub* poleis are those which are easier to ship *From*. We compute hub and authority centralities, $\mathbf{e}^{hub}$ and $\mathbf{e}^{auth}$, respectively, in addition to right eigenvector centrality for our directed weighted network as follows:

$$\mathbf{e}^{auth} = \beta_A \mathbf{T}^{*\prime}\mathbf{e}^{hub}, \;\; \mathbf{e}^{hub} = \beta_H \mathbf{T}^*\mathbf{e}^{auth}, \tag{14}$$

where $\mathbf{T}^*$ is defined in (43). Therefore, hub centrality is defined in terms of the sum total for each node of what is "demanded" by the authority side of all other nodes, total exports. Authority centrality is defined in terms of the sum total of what each node "demands" from the hub side of all other nodes, total imports. Authority and hub centrality have to be consistent with one another. By combining the equations in (14) we find that *authority centrality*, $\mathbf{e}^{auth}$, is defined as the Perron-Frobenius eigenvector of $\mathbf{T}^{*\prime}\mathbf{T}^*$. Since this matrix is symmetric, its maximal eigenvalue defines the respective eigenvector. Hub centrality is given by (14) as $\mathbf{e}^{hub} = \mathbf{T}^*\mathbf{e}^{auth}$. Although Kleinberg authority and hub centralities do not originate specifically in our model, they are intuitively appealing. It thus follows that *authority centrality*, $\mathbf{e}^{auth}$, is the principal eigenvector of $\mathbf{T}'\mathbf{T}$; *hub centrality*, $\mathbf{e}^{hub}$, is the principal eigenvector of $\mathbf{T}\mathbf{T}'$. The matrices $\mathbf{T}\mathbf{T}'$ and $\mathbf{T}'\mathbf{T}$ have the same maximal eigenvalue, the Perron-Frobenius root. Again, for the purposes of the empirical analysis, it is important to note that lower numerical values of shipping costs denotes "economic proximity," and therefore greater values of the components of the centrality vectors that we compute denote greater centrality.

The *eigenvector centrality* measure encapsulates rich information about shipping costs.

Since the network of poleis connections is defined in terms of shipping costs, the measure implies that polis centrality is greater, the smaller are the shipping costs *To* the polis. This follows from the definition, under the assumption that $A_j = 1, \forall j$ and $\sigma = 2$.

It is also interesting to work with an ad hoc measure that expresses plain geography, the matrix of inverse shipping costs, $\mathbf{T}$ :

$$\mathbf{T}_{ij} = 1/\tau_{ij}. \tag{15}$$

This is a simple intuitive extension of the original binary adjacency matrix on which centrality measures are typically based. Being independent of productivities, it is a pure measure of connectedness, a measure of interaction. The centrality measures associated with (43), which is part of the equilibrium solution and proxies for trade interactions that contribute to incomes, are relevant for script adoption and coinage issue. Put it differently, the pure measure of connectedness, defined by (15), could capture both the potential to earn income because of trade and the ease in the diffusion of ideas along with trade. Measures based on (43) reflect the impact of shipping costs on general equilibrium outcomes and therefore capture mainly the impact of trade.

Centralities computed with (43) are referred to, in the remainder of this paper, as *stochastic centralities,* and those computed with (15) as *non-stochastic centralities.* Apart from the stochastic versus non-stochastic alternatives, we also have poleis versus segment centrality. The poleis centrality is computed with the sample of all poleis in our data, and the segment centrality is computed with the sample of evenly spaced segments around the Mediterranean and Black Seas. The former is a more accurate measure of centrality, while the latter is a more exogenous measure of centrality that gets rid of the endogeneity of polis locations.

# 4 Data and Estimations

The system of equations (9) accounts for the evolution of script adoption decisions. It also serves to define the times till adoption as first-passage times of the underlying stochastic system. Furthermore, as the discussion of coinage issue decisions and their timing makes clear, those decisions are amenable to similar treatments. This modeling helps to motivate our estimations, which we conduct by means of separate discrete choice and survival models. Script adoption and coinage issue may also be interdependent, and indeed we discuss this in the context of the data in sections 4.3 and 4.3.1, with "atemporal" estimations following further below in section 4.3.2, and full dynamic analyses of the spatial evolutions of adoptions given in sections 4.5.1 and 4.5.2.

## 4.1 The Poleis Data

We explored the Polis Project data from http://polis.stanford.edu/ extensively, which utilizes information from *the Inventory of Archaic and Classic Poleis* [Hansen and Nielsen (2004)], a compilation of the entirety of the archaeological and historical data for about 1035 archaic and classical Hellenic cities by the Copenhagen Polis Centre. Figure 2 shows the map of poleis used in this paper's analysis. Some of the data were digitized by Josiah Ober and his team of Stanford and Oxford scholars. Important variable are: region (namely historical region), colonies and colonizers, Delian (participation in the Delian League), and *Koinon* (participation in a federation).[28] We have used the GPS coordinates in the data to merge them with micro-geographic information, including ruggedness, malaria index, temperature, precipitation, and elevation. The ruggedness index is from Nunn and Puga (2012), the malaria index is from Kiszewski *et al.* (2004), the crop suitability data is from Zabel *et al.* (2014), and temperature, precipitation, and elevation are from WorldClim (https://www.worldclim.org/data/worldclim21.html).

Our data on the times of first issue of coinage come from two sources. One, which is available in the original database of the Stanford Polis Project, records time of issue by century; the second, which we hand-coded ourselves, uses the more detailed information

[28] While the Delian League is the hegemonic role of Athens in it is well known, the *Koinon* is less well known. This refers to participation in a form of regional city state federations in ancient Greece comprised of several poleis and in some instances other forms of community, and characterized by the division of sovereignty among the regional government and its constituent communities. As MacKil (2013) puts it, such participation was a remarkably widespread phenomenon, with almost of mainland Greece and the Peloponnese becoming part of a *Koinon.* See Economou *et al.* (2015).

available in Hansen and Nielsen, *op. cit.,* either according to attested approximate year or approximation by interval midpoints. Silver coinage is the most prevalent form, with 339 vs. 187 observations, followed by 284 vs. 148 for bronze. Figure 3 shows the locations of poleis with coins. In the simple cross-sectional probit model for coinage, we define the coinage issue indicator using either source. But for the survival and pseudo panel analyses, we exclude the poleis for which we only know the date of coinage by century only. Gold and electrum coinage are much rarer. In our data 21 poleis issued gold coins and 9 poleis issued electrum coins. However, the classics literature has concluded that electrum coins were the first ones to be issued; see Hodos (2020), Ch. 3, and Kallet and Kroll (2020).

It is tempting to treat silver and gold coins as substitutes. They are both made of precious metal with much higher intrinsic value than bronze and were used as money first, indeed originally in the form of bullion or *Hacksilber* [Kroll (2013)]) in trade prior to the invention of coinage. Bronze coins seemed to have been used very differently. They were issued both by larger poleis in small denominations to facilitate retail trade, and by smaller ones because they were cheap to manufacture, but still served as unit of account and medium of exchange. Several poleis issued multiple types of coins during their history. In the present version of the paper, we do not differentiate the type of coin and consider only the earliest date of coinage issue.

The script data are from the *Poinikastas Database.* We get the earliest date when each local script is attested, and match it with our poleis data. Our database of scripts is composed of 151 scripts attested with individual poleis, and 23 regional scripts. See figure 4 for the locations of poleis with scripts.

## 4.2 Shipping Costs

Our shipping costs consist of two components. The first component is the pairwise shipping cost across coastal sites around the Mediterranean and Black Seas. With the help of the Tufts Data Lab team, we construct 2737 evenly spaced segments that cover the entire coastline of the Mediterranean and Black Seas; the sailing times for all coastal segment midpoint–pairs are based on wind speeds and parameters from Whitewright (2011). The coastal midpoints are about 15km away from each other. Further details are given in the Appendix of Chen, Ioannides and Rauch (2021).[29]

The second component is constructed from overland shipping costs in the form of walking times, based on Özak (2010), `Human Mobility Index`. Using Özak's cost surface we compute the overland cost among all poleis and the cost between each polis and their nearest coastal sites. [30] Thus, we account for the differential costs of shipping by assuming travel costs, in hours, between inland points $a$ and $b$ in the form:

$$\text{cost}_{a,b} = \min\{\gamma * \text{walking}_{\ a,b}, \gamma * \text{walking}_{\ a,A} + \text{sailing}_{\ A,B} + \gamma * \text{walking}_{B,b}\}, \tag{16}$$

where parameter $\gamma$ adjusts upwards the cost of overland traveling relative to maritime traveling; $(A, B)$ denote coastal segments nearest poleis $a$ and $b$, respectively. For the baseline analysis, we use $\gamma = 5$. We use such relatively small parameter values out of two considerations: first, the above cited 1:40 parameter range is assessed for the price of goods transportation, but the cultural transmission might be less costly; second, if parameter $\gamma$ is too large, the travel cost will capture mainly the distance to the coast and will have less variation. We also tried alternative traveling cost parameter values: $\gamma = 0, 10, 20$. When $\gamma = 0$, only the maritime shipping cost is included. Results are qualitatively similar to results with $\gamma = 5$ and are available in online appendix.

## 4.3 Adoption of Script and of Coinage Issue as Joint Decisions

Interpolis trade is facilitated by both script adoption and coinage issue, although both of them might not have been present at all instances and times. The interest of local rulers were served by both innovations. E.g., some of the earliest written records are in the form

[29]The wind data come from a NASA site:
https://podaac.jpl.nasa.gov/dataset/CCMP_MEASURES
_ATLAS_L4_OW_L3_5A_MONTHLY_WIND_VECTORS_FLK
and was averaged over all available years (1987 to 2011).

[30]Overland shipping was known to be much costlier than maritime shipping; as Bresson (2016) Ch. 3, p. 80, states: "Clearly, the cost of overland transport was much higher. A relationship of 1 to 40 has been proposed, based on prices mentioned in Diocletian's *Edict on Maximum Prices* in the late Roman Empire".

of tablets resembling modern spreadsheets, that seem record transactions, such as those from ancient Uruk, Iraq [ Robinson (2009), p. 10-12]. The Linear B tablets also record transactions, mainly in the form of interactions with the state pertaining to tax revenue, assignment of contract work or military conscription. Issue of coinage and the need to fight counterfeiting was critical for ability of rulers in ancient Asia Minor, especially Lydia, to finance the operations of the state.

There is evidence that adoption of script might predate the issue of coinage: indeed in our data 23 poleis only are attested with coinage predating script, among the total of 148 poleis that have data on both the first issue of any type of coinage and script; see Figure 5. Figure 6 also suggests that scripts generally predate coinage, but notably early coins were not always imprinted with writing.[31] In addition, figure 7, the plots of cumulative density function of the date of first coin issued separately by whether a poleis have ever adopted a script, shows that among all poleis that have issued a coin, compared with the group of poleis that have never adopted any script, the group of poleis with script generally issue their coins earlier, since the CDF of the former group is always above that of the latter group. Therefore, it is fair to say that scripts might have augmented TFP and therefore growth, and hence promoted the issue of coinage. Adoption of script and issue of coinage might also be jointly determined, by factors like trade, which we take up further below.

### 4.3.1 Cross-tabulations for Scripts and Coins

Table 1 reports a two-way tabulation of the number of poleis with scripts and with coinage. Figure 6 is a scatter plot of the dates for scripts and coins for poleis that have both. Few poleis in our data issued coins earlier than adopted scripts, but that is partly because the date of scripts is truncated (no points in the bottom left area). As mentioned earlier, the formal adoption of the Ionic script by Athens in 403/402 BCE effectively ends the diffusion of scripts. Table 2 reports the count of observations based on script adoption and coinage.

The sample is made up of 7 groups: i. Poleis with neither script nor coinage (397

[31] Indeed, coinage without scripts did exist. Aeginetan coinage is a case in point. See Pavlek (2021) for details on the informational role of images on coinage.

observations); ii. Poleis with no script but with coinage (85 observations); iii. Poleis with script but no coinage (382 observations, due to our assignment of scripts to poleis via regional scripts); iv. Poleis with both script and coinage, but with script adoption preceding coinage issue (116 observations); v. Poleis with both script and coinage, but with script adoption following coinage issue (23 observations); vi. Poleis with both script and coinage, but with script adoption and coinage at the same time (9 observations); vii. Poleis with coinage, but with the exact issue date being unknown (i.e., we only know the dates in terms of centuries) (204 observations). The last group is excluded for most analyses that require timing information.

#### 4.3.2 Does Script Adoption Affect Issue of Coinage?

The cross-tabulations reported on Table 1 and the plots in Figures 5, 6 and 7 do suggest that poleis that did issue coinage are more likely to have already adopted scripts. Also, Figures 5 and 6 show that script adoption generally predates coinage. Coinage often (thought not always) did carry brief inscriptions identifying their issuer, often abbreviated, like Athens was identified as $A\Theta E$ on the famous *tetradrachm*, or other insignia and symbols of the respective poleis and their dieties.[32] Therefore, coinage issue should not presuppose availability of script. Pappa (2019) makes the provocative argument, namely that literacy by providing for ways to establish trade credit might not have promoted issue of coinage and indeed might have even discouraged it.[33]

Next we seek to establish such a potential relationship by controlling by means of a number of covariates that are suggested by our theory. We thus estimate the following equation:

$$\text{Coin}_i = \alpha_0 + \alpha_1 \mathbb{1}\{\text{Script}_i\} + \beta \mathcal{X}_i + \varepsilon_i, \tag{17}$$

where the dependent variable is defined as $\text{Coin}_i = 1$, if polis $i$ has ever issued coinage, and $= 0$, otherwise. The key explanatory variable is defined as $\mathbb{1}\{\text{Script}_i\} = 1$, if for polis

[32]And yet, Aegina's very famous coins carried the relief of a sea turtle on the obverse and that of an incuse square on the reverse, and did not include any lettering. See also Pavlek (2021) for the informational role played by images.

[33]We were unaware of Pappa (2019) when we started this investigation.

$i$ has adopted a script, and $= 0$, otherwise; the vector of controls $\mathcal{X}_i$ includes measures of centrality and the full battery of microgeographic information that we have used in previous regressions; $\varepsilon_i$ is the error term.

Table 3 reports the probit regression results. The unconditional regression in col (1) of Table 3 confirms the observation from Table 1 that script adopters are also more likely to issue their own coins. Col (2) - (5) gradually add in more control variables, including geographical variables, centrality variables,[34] Delian and Federal State memberships, and polis size. Those variables can affect both script adoption and coinage. We obtain positive and significant coefficients for script indicators in all those specifications. In other words, even after controlling for trade potential (via centrality) and for local geography, we still find a strong positive correlation between script adoption and coinage issue. Furthermore, script adopters are more likely, by 38 to 65 percentage points, to issue coinage. In addition, in Table 4, we use the date of first coinage issue as the dependent variable. Again, consistent with Figure 7, there is a positive relationship between script adoption and date of coinage after controlling for trade potential and for local geography. Among the poleis that have issued coinage, script adopters on average issue their coinage 39 to 53 years earlier.

As a robustness check, in Table S4 of online appendix, we include the poleis for which we only know their coinage issue date by century and use the century of coinage issue date as the dependent variable, and again find script adopters on average issue their coinage 23 to 40 years earlier. We think the results are consistent with the main results in Table 4, as the smaller coefficients can come from measurement error.

We do not find evidence supportive of Pappa (2019), namely that the emergence of alphabetic writing (literacy, in her words) allowed the recording of trade credit and therefore might have obviated, up to a point, the need of a physical form of money, coinage. Even conditional on the potential to trade (centrality and Delian and Federal state membership) and state capacity (indirectly, via geographical variables and directly via polis size), we find script adoption is associated with greater probability and earlier date of coinage.

[34] In Table 3 and Table 4, we use stochastic centrality based on the poleis sample. But we also show in our online appendix that the results are robust to controlling for alternative centrality concepts.

### 4.3.3 Does Centrality Affect Epichoric Script Adoption and Issue of Coinage Differently?

We explore next whether general aspects of location, namely as proxied by our centrality variables, affect script adoption and issue of coinage differently. Centrality measures the trade potential of a polis and how easily it may reach, or be reached by, other poleis. However, script adoptions and coinage issuance may be determined by other, possibly the same, unobserved factors, such as state capacity. To account for such possibilities, we use bivariate probit and seemingly unrelated regressions models to estimate the impact of centrality in the presence of such unobserved interdependence. We would expect that higher values of centrality increase the likelihood for a polis to adopt a script, which is in effect a beneficial public good. Issue of coinage is affected by other factors, too, that is not only participation in trade but proximity to mine of precious metals and state capacity, more generally, too.

Table 5 reports the bivariate probit results. The dependent variables are binary indicators for script adoption and coin issuance. The effects of stochastic centrality on script adoption and coinage issue are in opposite directions. The effects of non-stochastic centrality show a different pattern: for script adoption, how a polis can be reached by other poleis matters more, whereas for issue of coinage, how a polis can reach other poleis matters more. We see this since for script adoption, the left eigenvector and authority centralities are more significant than the right eigenvector and hub centralities. The former two centralities are measures of how a polis is connected *from* other poleis, which supports the notion of diffusion from previous adopters. The latter two centralities measure how a polis is connected *to* other poleis. For issue of coinage, the right eigenvector and hub centralities are more significant than the left eigenvector and authority centrality. This result accords with intuition, if we think of script adoption as tacit: people are passively affected by the adoption of a new idea, the script, by scribes, whose full utilization and diffusion however does require learning. Issue of coinage involves deliberate state action. The negative impact of centrality on coinage issue may operate via a polis size and its state capacity.

Tables 6 and 7 report results with seemingly unrelated regressions. The dependent variables are the dates of script adoption and coinage issue. The impacts of centrality are similar to those obtained with the bivariate probit models. More centrally located poleis adopt scripts earlier but issue coinage later. Table 6 reports results with a sample that includes poleis for which coinage dates are attested by century only (and we set adoption dates at the respective midpoint). The sample for the regressions of Table 7 excludes those poleis. Consequently, in Table 6, the dates of coinage issue have larger measurement error, but it is reasonable to think of them as classical measurement error. In Table 7, the dates of coinage issue have smaller measurement error, but the sample size is considerably smaller, 146 instead of 307 observations.

### 4.4 Estimations with Survival Models

We next report results with two types of estimations for the emergence of scripts and issue of coinage. As discrete events with date information they easily lend themselves to similar treatments. One is a discrete choice estimation of whether a polis has been attested with a script, and jointly with the time of its occurrence; a second is a discrete choice estimation of whether a polis has been attested to have issued coinage, and jointly with the time of its occurrence. Although we experimented extensively with such joint modeling, an estimation model that accounts for both events jointly in reduced form is the survival model. An unobservable index determines the likelihood that an event occurs. However, because the study periods for both events are finite, and different for script adoption and issue of coinage. an event might not be observed for every polis. That is, the survival analysis must deal with censored data. We apply the survival model both for the adoption of epichoric scripts and for coinage issue.

Let $(t_i, d_i)$ denote the time till polis $i$ is attested to have an epichoric script and $d_i$ the corresponding censoring indicator: $d_i = 1$, if an epichoric script is attested at time $t_i$, and $d_i = 0$, if it is censored.

Let $f(t), t > 0$, denote the probability density function of the time till adoption, $T$, and

$F(.)$ the corresponding cumulative distribution function. The survival function is

$$\text{Su}(t) := Prob[T > t] = \int_t^\infty f(x)dx = 1 - F(t).$$

The value of the survival function denotes the probability that an epichoric script has not been attested by time $t$. The hazard function defines the probability that a polis that has not adopted by time $t$ is attested to adopt in interval $(t, t + \delta t)$ :

$$\lambda(t) := \frac{\text{Prob}[t < T < t + \delta t | T > t]}{\delta t} = \frac{f(t)}{S(t)} = \frac{\partial \text{Su}(t)}{\partial t} \frac{1}{\text{Su}(t)}.$$

The cumulative hazard function, $\Lambda(t) := \int_0^t \lambda(t)dt$, and the survival function satisfy: $\text{Su}(t) = \exp[-\Lambda(t)]$.

If $\log t_i$ is parameterized as $\log t_i = \mathbf{x}_i\beta + z_i$, where $\mathbf{x}_i$ is a vector of covariates, and $\beta$ the respective vector of parameters, and $z_i$ is assumed to be normally distributed, then the lognormal survival model follows. Similarly, if $z_i$ is assumed to have a logistic distribution, then the loglogistic survival model follows. Both those assumptions are roughly compatible with the scatter plots of the data.

The respective survival and density functions for the lognormal survival model with the mean of $\ln t$ parametrized by $\mathbf{x}_i\beta$ and the associated variance of $z_i$ denoted by $\text{Var}_z$ are:

$$\text{Su}(t) = 1 - \Phi \left\{ \frac{\ln t - \mathbf{x}_i\beta}{\sqrt{\text{Var}_z}} \right\}; \quad f(t) = \frac{1}{t(2\pi \text{Var}_z)^{\frac{1}{2}}} \exp \left[ \frac{-1}{2\text{Var}_z} \left\{ \ln t - \mathbf{x}_i\beta \right\}^2 \right],$$

where $\Phi$ denotes the standardized normal cumulative distribution.

The loglogistic case is estimated by specifying its parameters $\varpi = \exp[-\mathbf{x}_i\beta]$ and $\delta$. The respective survival and density functions are:

$$\text{Su}(t) = \left[1 + (\varpi t)^{-\delta}\right]^{-1}; \quad f(t) = \frac{\varpi^{-\delta} t^{(\delta-1)^{-1}}}{\delta \left[1 + (\varpi t)^{-\delta}\right]^2}.$$

Both survival estimation procedures allow estimation of a frailty parameter, the survival model counterpart of random effects. We specify frailty via a gamma distribution with parameters $(\vartheta^{-1}, \vartheta)$.[35]

### 4.4.1 Estimations of Adoption Dates for Epichoric Scripts

We work as follows with the epichoric scripts data that we have obtained from the *Poinikastas* Database[36], a digitization of the entire archive underlying Jeffery and Johnston (1990). The dates of attested adoption range from 725 BCE to 416 BCE.

We define the survival times from 726 BCE, so that survival time for an attested date $t_i$, is $t_i - (-726)$. For instance, for a polis that adopts at -725, that is, 725 BCE, the survival time is equal to 1, and its log is equal to 0; for a polis that adopts a script in 450 BCE, the survival time is is 726 - 450 = 276. So, the later an adoption occurs, the greater the survival time. For the purpose of the survival analysis we assume that adoption times are censored at 400 BCE [D'Angour (1999)].

We examine robustness by considering two additional starting dates, one is 776 BCE, the legendary date of the first Olympic Games in Ancient Olympia, and the other is 1050 BCE. The case for an earlier transmission of the alphabet to the Hellenic world prior to the first attested written record, which in our data is 725 BCE, has been made quite forcefully recently by a number of authors, including Waal (2020) and Bourogiannis (2018). The results are avaiable in Table S14 and S15 of our online appendix and are pretty similar to our main results here.

Our data set consists of adoption times by poleis for 174 epichoric scripts. Since some scripts are associated with the regions where poleis lie, 692 poleis may be matched with at least one script. Among them, 151 poleis are directly matched with a script, that is, not via their regions.

Our model of script adoption leads to the prediction that in the stochastic steady state adoptions cluster. At first glance, the model is confirmed by the original Kirckhoff map, as modernized: Figure 1. Next we select a number of poleis, which are near to, or coincide with, sites that scholars think are likely to have been where the diffusion of the scripts started in

[35]Stata `streg` Manual, p. 378.
[36]http://poinikastas.csad.ox.ac.uk/

the Hellenic world. Specifically, Eretria and nearby Lefkandi (which is not a polis in its own right) are directly linked to early transmission of the Chalkis/Kyme (Euboean) script to the Italian peninsula (Magna Graecia); Athens (Athenai) was an early cosmopolitan place, with a lot of cultural and economic activity; Thera is specifically mentioned in the literature; and several poleis in Crete are also mentioned, and therefore Herakleion may proxy for them;[37] Rhodos is a candidate on its own right as well as a proxy for the coastal sites in the Middle East, including all of the Phoenician poleis, and of course sites in Cyprus, all of which lie to its east.[38] The latter three poleis are attested for having hosted bilingual communities of Greek and Phoenician traders.

Since the distances among sites are highly correlated, it would be problematic to include them together in regressions. Instead, we propose a simple aggregation, which is a market access-style (i.e, sum of inverse distances) proximity measure to them as a group, generically defined as $\mathcal{S}$. Empirically, it is defined as:

$$\text{MA: } \mathcal{S}_i = \begin{cases} \sum_{s \in S} 1/d_{i,s} & \text{if } i \notin \mathcal{S}; \\ \sum_{s \in \mathcal{S} \setminus i} 1/d_{i,s} + \max_j \{1/d_{j,i}\} & \text{if } i \in \mathcal{S}. \end{cases} \tag{18}$$

We use variables thus defined and referred to as *MA: Potential Origins*, which includes the five sites mentioned above, and *MA: Phoenician Sites*, which includes 30 Phoenician colonies around the Mediterranean, in order to test the overall importance of those potential sites of origins.

Table 8 reports the survival regression results for script adoption dates. We do not observe a significant impact[39] of proximity to Phoenician colonies (mapped in Figure 8) as a group, unless we introduce crop suitability variables, in particular, barley, millet and summer and winter wheat. This might be due to efficiency improvement associated with the inclusion of crop suitability variables. Once we do that then greater distances (that is smaller market access) from Phoenician sites are associated with earlier script adoption.

[37]See Jeffery and Morpurgo-Davies (1971).

[38]See Woodard (1997), Ch. 7, who argues in favor of a transition from Cypriot syllabaries to the epichoric scripts.

[39]This is also occasionally the case in some of our robustness specifications in online appendix.

We conjecture the reason to be that the negative impact of being further away from the center of the ancient Hellenic world outweighs the potential positive impact of being close to Phoenician colonies. We find it particularly interesting that this continues to be the case when we control for proximity of a polis to those particular poleis which scholars think might have been the origin of the script diffusion, mentioned above and referred to as potential sites of origin, or *potential sites* for short. Greater distances (that is, smaller market access) from sites of potential origins are associated with later script adoption. Market access to those sites increases the likelihood of earlier adoption, with the Script MA variable being highly statistically significant. We get the same results no matter if the script MA variable is computed in terms of distances *To* the poleis or *From* the poleis. This finding is in agreement with conjectures by scholars that the invention most likely took place at a location where Greek and Phoenician speakers mingled. However, the elasticity [40] is slightly larger when script MA is computed in terms of distances from the potential origins to the poleis. Being 1 standard deviation closer from a polis itself to those sites is associated with 36% reduction in the time until adopting a script. Being 1 standard deviation closer from those sites to a polis itself is associated with 41% reduction in the time until adopting a script. The overall location also matters: being central within the trading network is associated with earlier adoption of script.

We consider the role of centrality by exploring definitions in terms of two alternative samples: one, all poleis in our database, and, two, all equally-spaced segments around the Mediterranean sea. The former is a better measure of the actual centrality for poleis, while the latter is a more exogenous measure, as it is not based on other poleis' actual locations, which reflects endogeneity of urban development and therefore to a polis' own location. The results are not very different between those two alternative centrality measures. Moreover, connectedness from others, the *To* measure, is more important than being connected to others, the *From* measure. That is, authority centrality, which measures being connected *To*, is more significant than the hub centrality, which measures being connected *From.* When

[40] We compute the elasticity as the coefficient times the standard deviation of the explanatory variable. This is because the level of the centrality is not too meaningful as the eigenvector can be scaled up and down. Besides, the survival model is estimated using lognormal model, and thus the coefficient can be interpreted in terms of percent change in the depdendent variable.

market access from potential sites to a polis is included, the authority centrality is less significant. This may have to do with the fact that the five poleis deemed as potential origins are located in quite central places; see Figure 8. In fact, the correlation coefficient between authority centrality and Script MA from the potential origins to a polis is 0.71. The result that *To* matters more than *From* may reflect the fact that script diffusion was more of a passive process. We note a drawback associated with our use of the market access measure instead of controlling separately for distances from distinct sites. That is, this approach does not allow us to identify a possibly most likely site from which the innovation diffused, if indeed there might have been a single one.

In sum, our main results are that shorter distances of a polis from the poleis of potential origin are associated with earlier script adoptions, and so are the respective centralities and in both cases significantly so. They thus provide crucial confirmation for arguments widely discussed by the classics literature. The contextual information that Phoenician presence in some of the sites is bolstered by additional textual evidence. E.g., the verb *ποινικάζειν*, interpreted as "to write in the Phoenician manner," and the noun *ποινικαστάς*, interpreted as "scribe," are clearly very suggestive [Jeffery and Morpurgo-Davies (1971)].

#### 4.4.2 Estimation of Dates of Coinage Issue

We work in like manner with the time till issue of coinage as the dependent variable. Once coins have been issued, "struck," they typically remained in circulation for a long time, as witnessed by the cases of the Athenian *tetradrachm* and of coinage issued by Aegina, both of which continued circulating into the late antiquity. So, unlike with the adoption of epichoric scripts, which are attested in the historical record but come into disuse after the Ionian script was effectively adopted (following the lead of Athens) by many Hellenic poleis, coins would retain their value, as money as well as because of the intrinsic value of their precious metal content for many years, and indeed centuries.

Survival times are defined similarly to the scripts, except that the time range for coinage issue in our data is 610 BCE to 280 BCE. The origin is 625 BCE. To give an example, for poleis which issued their first coinage in 610 BCE, the survival time is $610 - (-625) = 15$. A positive coefficient implies that the larger the value of an explanatory variable, the longer the survival time and the later a polis issues its first coinage. We estimate survival models for the time when a polis issues its first coinage, regardless of the type of coin (gold, silver, bronze, or electrum), and assume the data are censored at 250 BCE.

Key regressors we consider in estimating survival models are the distances from a number of other poleis, the polis' own centralities, membership in the Delian League, and in a Koinon (Federation) prior to 330 BCE. The former is used to investigate the role of distances to poleis that are known to have issued coinage early, or in view of their proximity to known precious metal mines. If we think of coinage as an innovation, then the idea may gradually diffuse. In that case, the distance to places like Sardis in Lydia (the commonly acknowledged polity to have been the first one to issue coinage in the vicinity of the ancient Hellenic world [Hodos, *op. cit.*]) should be positively correlated with the date of coinage issue. Distances to known mines determine ease in the acquisition of precious metals needed in making coins and in effect proxy for supply of precious metals. Like with the script survival analysis, since the distances are highly correlated, we use a market access-style variable, *MA: Origins/Mines* for short, to reduce the dimensionality. Measures of centrality are also included to explore the role of trade in the acquisition of coins (and/or metals). They are also important proxies for polis size.

The regressions reported in Table 9 employ a sample that excludes poleis with coinage dates that are attested at the century-level. Thus, the comparison is between poleis for which we know the relatively more precise date of coinage and poleis for which we know that no coinage was issued during the period of available observations.

Proximity to particular poleis (namely Akanthos, Amphipolis, Ilion, Kyzikos, Lampsakos, Phokaia, and Sardis) that are presumed to have served as origins of diffusion, or with known mines, is beneficial for issuing one's own coins.

Centrality also matters for coinage, but notably in very different ways compared with for script adoption. All centrality variables have estimated coefficients which are positive, implying that more centrally located poleis issue coinage later or are less likely to issue.

The hub centrality is generally more significant than the authority centrality. Recall that hub centrality represents how a poleis is connected from itself to others. Hub centrality being more significant than authority centrality might reflect the fact that coinage is more of a deliberate choice involving state action. The positive sign of the coefficient could come from the resource competition. Another possible explanation for the positive coefficient for centrality is that coinage is positively correlated with the size of the polis, while the size of a polis is negatively correlated with centrality.

Delian League membership always has negative and significant coefficients. Membership in a Federation (Koinon) has positive but not very significant coefficients. When poleis with century-level coinage dates are included in the analysis, membership in a Federation has negative and significant coefficients. However, the coefficients for membership in a Federation are smaller in magnitude than those for Delian League membership. See online appendix for details about the table.

The empirical results for coinage issue are persistent in connection with membership in the Delian League. This suggests that the Athenian *Coinage, Weights and Measures Decree*, which aimed at standardizing coinage and standards among the member poleis of the Delian League, was indeed effective.[41] The use of Athenian silver coinage, weights and measures was made obligatory in all allied states under the hegemony of Athens [Hansen and Nielsen, *op. cit.*, p. 111]. Although the exact date is unknown and is inferred to be between 450 BCE and 447 BCE, the decree required that all allied coinage be taken out of circulation and melted down to be replaced by Attic coinage, while in the process allowing for the Athenian mint to extract substantial seignorage [Kallet and Kroll (2020), p. 31–34, 111–119,141–145]. After the decree was enacted, use of Athenian coinage became increasingly common, especially by smaller poleis. Members of Federations issued coinage in laissez-faire manner rather than being induced to do so by the *force majeure* of a coinage hegemon.

[41] Interestingly, this is in agreement with Plato's normative prediction that states should have a local, epichoric, coinage along with a general Hellenic one that would be valued outside the polis [Plato, *Laws,* 5.742a-b, quoted by Hodos (2020), Ch. 3].

## 4.5 Spatial Evolution of Script Adoption and Coinage Issue Decisions

Figure 11 plots the adoption curve for scripts based on raw data. The vertical axis is the cumulative number of poleis adopting a script, and the horizontal axis is the adoption date, ranging from 725 BCE to 416 BCE. Similarly, Figure 12 plots the adoption curve for coinage. Our observations for dates of coinage issue by poleis lie between 610 BCE and 280 BCE. In the following two subsections, we report estimation results which are obtained by organizing the data in the form of "pseudo panels." Appendix B discusses some particular aspects of the data that bear upon these estimations.

### 4.5.1 Spatial Evolution of Script Adoption Decisions

We focus on the spatial evolution of adoption of epichoric scripts by organizing the data in the form of a pseudo panel and adapting equation (9) to linear regression settings. That is, we break the entire length of the study into 6 periods.[42] The grouping into periods is not intended to be meaningful; it is merely intended to arrange the observations so that we have about the same number of new script adoptions in each period. The key explanatory variables of interest are distances *From* and *To* poleis that did or did not adopt in preceding periods.

We define the variables $\text{Script}_{i,t} = 1$, if polis $i$ is attested as adopting a script in period $t$, and $= 0$, if polis $i$ has not adopted a script up to time $t$. In other words, if a polis develops a script in $t = 3$, $\text{Script}_{i,3} = 1$, $\text{Script}_{i,2} = 0$, and $\text{Script}_{i,4} = .$, which implies that it is excluded from the analysis in period 4. This ensures that in each period we only compare the new adopters with non-adopters. We measure distances from previous script adopters by defining a market access style variable $\text{MAScript}_{i,t-1}$, which aggregates distances via the

[42]The 6 periods division is: period 1: [725–625BCE); period 2: [625– 610BCE); period 3: [610–537BCE); period 4: [537–500BCE); period 5: [500–475BCE); period 6: [475–416BCE]. The numbers of poleis adopting script in those periods are: 50, 179, 75, 156, 65, and 167, respectively. We cannot make the numbers more evenly distributed across periods, because of the existence of regional scripts. If a regional script is adopted in a period, that period will have a larger number of poleis adopting scripts.

sum of inverse distances from all previous script adopters:

$$\text{MAScript}_{i,t-1} = \sum_k \frac{\mathbb{1}\{Script_{k,q\leq t-1}\}}{\tau_{ki}}. \tag{19}$$

This definition conforms to the needs of a geography-adjusted adoption curves so that our pseudo-panel analysis corresponds to an adoption curve setting as proposed by Young (2009); see also Appendix B for a qualitative discussion of the data. In Young's contagion model, the adoption rate is a quadratic function of the share of adopters, $p(t)$ :

$$\dot{p}(t) = (\lambda p(t) + \gamma)(1 - p(t)). \tag{20}$$

Whereas Young (2009) assumes an infinitely large population and purely random encounters between individuals, our network is finite. Therefore, to get an empirical proxy the proportion of adopters $p(t)$, we normalize $\text{MAScript}_{i,t-1}$ by the market access to all poleis:

$$\text{MAScript}_{i,t-1} = \frac{\sum_{k\in Adopter_{t-1}} 1/\tau_{ki}}{\sum_p 1/\tau_{pi}}. \tag{21}$$

Intuitively, we can think of the normalized MA variable as the relative density of adopters around a poleis $i$. Clearly, the normalized $\text{MAScript}_{i,t-1}$ lies in $(0, 1)$. Another important benefit of this normalization is that we can interpret $1 - \text{MAScript}_{i,t-1}$ as the proportion of non-adopters:

$$\begin{aligned} 1 - \text{MAScript}_{i,t-1} &= 1 - \frac{\sum_{k\in Adopter_{t-1}} 1/\tau_{ki}}{\sum_p 1/\tau_{pi}} \\ &= 1 - \frac{\sum_{k\in Adopter_{t-1}} 1/\tau_{ki}}{\sum_{k\in Adopter_{t-1}} 1/\tau_{ki} + \sum_{g\in Nonadopter_{t-1}} 1/\tau_{gi}} \\ &= \frac{\sum_{g\in Nonadopter_{t-1}} 1/\tau_{ki}}{\sum_{k\in Adopter_{t-1}} 1/\tau_{ki} + \sum_{g\in Nonadopter_{t-1}} 1/\tau_{gi}} \\ &= \frac{\sum_{g\in Nonadopter_{t-1}} 1/\tau_{ki}}{\sum_p 1/\tau_{pi}}. \end{aligned} \tag{22}$$

Let $\mathcal{X}_i$ denote a vector of time-invariant local productivity variables, such as the ruggedness index, malaria index, precipitation, temperature, elevation, and crop suitability; and $\text{Period}_t$ period fixed effects. It is important to include period fixed effects, because as more poleis adopt scripts overtime, the script adopters are spatially denser, and $\text{MAScript}_{i,t-1}$ will grow larger for all poleis as time goes on. Inclusion of the period fixed effects will make our estimation "within period."

We adopt the contagion model of Young (2009), adapt it to our discrete time setting, and estimate the following model:

$$\text{Script}_{i,t} = a_0 + \lambda \text{MAScript}_{i,t-1}(1 - \text{MAScript}_{i,t-1}) + \zeta(1 - \text{MAScript}_{i,t-1}) + \beta \mathcal{X}_i + \text{Period}_t + \epsilon_{it}. \tag{23}$$

The model reflects two forces determining adoptions: one originates in poleis that have not yet adopted and are adopting by interacting with those that have, which is captured by the term involving parameter $\lambda$; a second originates from interaction with those that have not yet adopted, which may also pass information even though they have not adopted themselves. Its effect is captured by the term involving parameter $\zeta$.

Empirically, equation (23) is equivalent to including the linear and quadratic terms of $\text{Script}_{i,t-1}$:

$$\text{Script}_{i,t} = b_0 + b_1 \text{MAScript}_{i,t-1} + b_2 \text{MAScript}^2_{i,t-1} + \beta \mathcal{X}_i + \text{Period}_t + \epsilon_{it}. \tag{24}$$

Thus, we may also interpret the results as nonlinear effects of how poleis learn from those that have already adopted.[43]

Table 10 reports results of estimations of equation (23). We find that interaction with both adopters and non-adopters matters, as both $\text{MAScript}_{i,t-1}(1 - \text{MAScript}_{i,t-1})$ and $1 - \text{MAScript}_{i,t-1}$ have significant positive coefficients. Moreover, the coefficient for the former is larger than the latter. Therefore, the results suggest that in the diffusion of scripts, both adopters and non-adopters pass information. However, adopters have a stronger effect either because they have, and may pass, more information, or because there is a peer effect or

[43] Algebraically, of course, (Equation 23) and (Equation 24) are identical if one recognizes $b_0 = a_0 + \zeta$ , $b_1 = \lambda - \zeta$, and $b_2 = -\lambda$.

endorsement effect.

Table 11 reports results for equation (24). The fact that $\text{MAScript}_{i,t-1}(1-\text{MAScript}_{i,t-1})$ has a significiant coefficient already suggests the existence of nonlinearity: $b_2 = -\lambda$. To draw Figure 9, we select a few values of $\text{MAScript}_{i,t-1}$ (namely at 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, 99th percentiles), and compute the effects of proximity to previous adopters at those values. Here by "effect" we mean $(\partial\text{Script}_{i,t}/\partial\text{MAScript}_{i,t-1})|_{\text{MAScript}_{i,t-1}} = (b_1 + 2 * b_2 * \text{MAScript}_{i,t-1})|_{\text{MAScript}_{i,t-1}}$. Figure 9 shows that regardless of whether we measure proximity in terms of *To* or *From*, or whether we control for segment or poleis centrality, being too close to previous adopters is negatively correlated with the event that a polis adopts a script. After a distance threshold, it is beneficial to be close to previous adopters. One possibility is that poleis might have adopted the scripts of their nearest neighbors. We do not observe whether or not that might have even happened, since geographical proximity could be associated with closer dialects and thus lower costs of using the same script.

### 4.5.2 Spatial Evolution of Coinage Issues

Working in like manner we study the spatial diffusion of coinage issue by breaking up the entire length of the study again into 6 periods.[44] As in the preceding section, we define the following variables: $\text{Coin}_{i,t} = 1$, if polis $i$ issued its first coinage in period $t$, and $= 0$, if polis $i$ has not issued any coinage until period $t$; $\text{MACoin}_{i,t-1}$ is defined as the coinage counterpart of $\text{MAScript}_{i,t-1} = 1$, that is, as the sum of inverse distances from all previous coinage issuers, scaled by market access from all poleis; the vector $\mathcal{X}_i$ again includes time-invariant productivity variables associated with the site of polis $i$.

Table 12 and Table 13 report the estimation results. We find similar results to those of the script pseudo panel analysis. Again, previous issuers have a stronger impact compared with non-issuers. A major difference is that polis size has a strong impact on coinage issue and its inclusion makes the quadratic term in Young's contagion model lose its significance.

[44]The 6 periods are: period 1, [610–489BCE); period 2: [489–449BCE); period 3: [449–409BCE); period 4: [409–374BCE); period 5: [374–349BCE); period 6: [349–280BCE]. The numbers of poleis adopting script in each period are 48, 40, 32, 36, 40, and 37, respectively.

The linear term in Table 13 is still significant even when size is also included. Regardless of the significance of the quadratic term, the net effect, as shown in Figure 10, is always positive for different values of $\text{MACoin}_{i,t-1}$. This is appealing: being close to other poleis that have issued coins implies a lower cost of gaining metal/coins from those poleis via trade.

# 5 Conclusions

The paper reports empirical results on the diffusion of adoption of epichoric scripts and of issue of coinage by Hellenic poleis, that is, ancient Greek cities. The epichoric scripts are the precursors of the Hellenic alphabet. Coinage is of enormous significance in its own right. Our empirical investigations utilize unusual and hitherto unexplored data, some of which we ourselves coded from the archaeological record, and are motivated by means of analytical results. In addition to novel use of network tools for the weighted directed network defined by the system of poleis and the travelling costs among them, the following empirical findings stand out.

One, script adoption generally predates issue of coinage. Descriptive evidence shows that unconditionally, script adoption is associated with higher probability and earlier date of issue of coinage. The same result holds firmly even while we control for a large set of covariates, including centralities and micro-geographic information.

Two, bivariate probit regressions with script adoption joint with issue of coinage suggest that being central in the trading network is associated with a higher probability of adopting a script, but lower probability of issuing a coin. In addition, how easily a polis can be reached by other poleis matters more for script adoption, while how easily a polis can reach other poleis matters more for issue of coinage. This might be explained by the fact that script adoption involves a tacit accommodation to a TFP shock, whereas issue of coinage involves deliberate state action. In the former case an innovation is tacitly adopted, whereas in the latter coinage issue is facilitated by specie inflow via greater exports. Estimations of determinants of adoption dates using seemingly unrelated regressions show again that the more centrally located poleis tend to adopt scripts earlier but issue coinage later.

Three, being closer to sites of potential origin of alphabetic writing, that is to such poleis as Athens, Eretria, Herakleion, and Rhodos (with the latter also proxying for sites further to its east) is strongly associated with earlier script adoption; being closer to Phoenician sites is associated with later script adoption, at least according to some of our specifications. A possible explanation for the latter observation is that the Phoenician sites are far from most poleis, and the negative effect associated with being distant in the trading network outweighs the positive effect of more interaction with the Phoenician sites. Similarly, being close to sites with known mines or potential origin of coinage is associated with earlier issue of coinage.

And, four, when we bring the contagion model of Young (2009) to the data we find that both forces of contagion are associated with earlier script adoptions and issues of coinage. That is, new script adoptions and issues of coinage are associated with interactions both with poleis that have not yet adopted a script and with those that have, and similarly for issues of coinage. Both types of interactions increase the likelihood of script adoption, or issue of coinage. However, for both script adoption and issue of coinage we find that interactions with the group of previous script adopters, or with issuers of coinage, have stronger effects than those with non-adopters or non-issuers.

Last, we note that the particular evidence on which this paper is based is a mere glimpse of how the invention of the Hellenic alphabet and its diffusion together with the invention of coinage served as crucial vehicles for information transmission and therefore amounted to innovations of overwhelming importance for human cultural evolution. Whereas coinage served not only economic but also political life as an information system [Pavlek (2021)], the convenience of alphabetic writing facilitated mass literacy and therefore all the extraordinary human developments that followed.

# 6 APPENDIX A: Autarky vs. Interpolis Trade Equilibrium and Issue of Coinage

This Appendix takes off from Casella (1992) and develops a model of the system of the ancient Hellenic poleis as sovereign entities, polities, that engage in trade and may issue commodity money, in the form of coinage. The coinage was minted originally in electrum, but later primarily in silver and to a lesser extent gold. Bronze was also used to strike coins of smaller denominations. Models of monetary economies, like that of Casella (1992), need minimal modification to allow for commodity money, namely essentially imposing a condition that the monetary value for the commodity used as a medium of exchange must exceed its intrinsic value [Champ and Freeman (2004), Ch. 2]. It is also straightforward to allow for the cost of coinage. In the remainder of the Appendix we adapt the two-country model of Casella (1992) to many poleis as sovereign polities, and assume interpolis trade takes place under the Armington assumption and is subject to shipping costs.

## 6.1 Interpolis Trade with Shipping Costs: Many Poleis

The present section is novel and combines the static model of Chen, Ioannides, and Rauch *et al.* (2021), itself a simplification of Allen and Donaldson (2018), but closely related to Allen and Arkolakis (2016). It is a dynamic model that retains the two-overlapping generations structure of Casella (1992), with money, understood as coinage issue, as the only asset.

Trade presumes information: there is ample historical evidence of awareness of the geographical extent of trade [Ioannides (2019); Chen *et al.* (2021)]. We assume that each polis produces a single differentiated good and employ the Armington assumption that goods are differentiated by origin, so that as many goods are traded as the number of poleis. Labor, supplied inelastically in quantity $S_i$, is the only factor of production in each polis $i$, and may be mobile, as in the so-called economic geography case, as we discuss briefly below [see also Chen *et al.* (2021)]. It may also be immobile, as in the standard international trade case. Each polis-specific good is produced with constant returns to scale according to the following production function

$$Q_i = A_i S_i, i = 1, \ldots, J, \tag{25}$$

where $A_i$ denotes TFP that may proxy for geographical features and local productivity attributes, such crop suitability, etc.

Individuals work when they are young and receive their nominal wage $w_i$, which they save in the form of coinage. In the second period of their lives they spend their money holdings on differentiated consumption goods. They have identical CES preferences, as in (2) above: they value a composite consumption good, defined as a CES aggregate of quantities of all $J$ goods produced in the economy,

$$H_i := \left( \sum_{j=1}^{J} c_{ji}^{\theta} \right)^{1/\theta}, \tag{26}$$

and a public good, whose quantity is $\Gamma_i$. The individual lifetime utility function in (3) is rewritten here as:

$$U_i = (1-g) \ln H_i + g \ln \Gamma_i, \quad , j = 1, \ldots J. \tag{27}$$

To the component involving $\ln H_i$, defined in (26 above, there corresponds an indirect subutility $\ln \left( \frac{Y_i}{P_i} \right)$, where $Y_i$ denotes nominal spending on the differentiated goods and $P_i$ the Dixit-Stiglitz ideal price index,

$$P_i := \left[ \sum_k \left( \tau_{ki} \frac{w_k}{A_k} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}, \ \sigma > 1, \tag{28}$$

where $\sigma := (1-\theta)^{-1}$, is the elasticity of substitution across intermediate varieties, $w_i$ is the equilibrium nominal wage, $\tau_{ij} > 1$ denotes shipping costs from $i$ to $j$, that is, the units of the good $i$ that must be shipped from origin site $i$ for one unit to arrive at a destination site $j$. Shipping costs combine overland travel costs and sailing times; due to wind patterns, the latter costs are asymmetric: $\tau_{ij} \neq \tau_{ji}$. We note that in spite of the "love for variety" expressed by CES preferences the given number of poleis implies a fixed number of goods. In the case of the Armington assumption with goods being differentiated by origin, the optimum value of the consumption subutility does not depend on polis size. That is so unlike the Dixit-Stiglitz model with monopolistic competition and endogenous number of goods, in which case it would depend on polis size. However, optimum utility does increase with the number of poleis in the entire system of poleis. This confers benefits from the expansion of the urban system though colonization. In any of the modes of financing the public good, its quantity does depend on polis size, which introduces dependence of individuals' welfare on polis size.

### 6.1.1 Autarky

In the case of autarky, the public good may be financed by polis-own coinage issue or a local tax. However the provision of the public good may be financed, it absorbs a share $g$ of the total output of each polis. With coinage issue and in the absence of trade, only the local good is consumed. Then: $w_i = A_i p_i$, $H_i = A_i(1-g)$, $\Gamma_i = gS_i$, and

$$V_{i,aut,nocoinage} = \ln\left[(1-g)^{1-g} g^g\right] + (1-g)\ln A_i + g\ln S_i. \tag{29}$$

In the case of coinage issue by polis $i$, the above expression is modified by subtracting the cost of coinage, $g\ln\mu_i$, from the r.h.s. of (29).

### 6.1.2 Interpolis Trade

For equilibrium in the goods market in polis $i$, the value of total spending, that is spending to provide the public good, $w_i\Gamma_i$, plus the sum-total of spending by all poleis including polis $i$, each of which demands

$$X_{ij} = \left(\frac{\tau_{ij}}{A_i}\right)^{1-\sigma} w_i^{1-\sigma} P_j^{\sigma-1} w_j y_j, \tag{30}$$

where $Y_i = w_i y_i$, must be equal to total income, $S_i w_i$. The polis issues new coinage in the amount $M_i$, whose nominal cost is $\mu_i M_i$ and uses to pay for the public good, $w_i \ell_{\Gamma,i} = M_i$. That is, $\Gamma_i = \frac{M_i}{w_i} := m_i$, the provision of the public good is financed by the inflation tax.

If poleis trade with one another by using their own coinage, each polis is subject to an equilibrium condition in the inter-polis exchange market: total payments to all other poleis must be equal to total receipts from it own sales. Such a condition must reflect exchange rates. This is much too complicated to deal with unless poleis treat the coinage of all other poleis on par, in which case all exchange rates are equal to 1. Otherwise, in the absence of such a system-wide monetary standard, the simultaneous existence of $J$ different types of coins and their respective exchange rates makes for a setting that is much too complicated to deal with for our purposes.

In the case of an agreed-to system-wide monetary standard, in other words a coinage union, nominal wages are equalized and they will thus be referred to without subscripts (except when accounting for lags/leads). This allows us to define the equilibrium values for real spending as functions of real money issues, that is the $m_i$'s, and exogenous variables. A real price index, $\tilde{P}_j := w^{-1}P_i$, follows:

$$\tilde{P}_i = \left[\sum_k \left(\frac{\tau_{ki}}{A_k}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}, \ \sigma > 1, \tag{31}$$

and the conditions for general equilibrium express that real spending on the public good and on the differentiated goods produced in $i$ and demanded by all poleis, $j = 1, \ldots, J$, is equal to local labor supply:

$$\mu_i m_i + \sum_j \frac{(\tau_{ij}/A_i)^{1-\sigma}}{\tilde{P}_j^{1-\sigma}} y_j = S_i, \ j = 1, \ldots, J. \tag{32}$$

The $J$ equations (32) define a linear system which yields the vector of real spending $\mathbf{y}$ as a linear function of the $S_i$'s and the $m_i$'s, as we clarify shortly.

Let

$$\tilde{\mathbf{T}}_{ij} := \frac{\left(\frac{\tau_{ij}}{A_i}\right)^{1-\sigma}}{\tilde{P}_j^{1-\sigma}} = \frac{\left(\frac{\tau_{ij}}{A_i}\right)^{1-\sigma}}{\sum_k \left(\frac{\tau_{kj}}{A_k}\right)^{1-\sigma}}, \tag{33}$$

denote the matrix whose row$-i$ enters the l.h.s. of (32), a column-stochastic matrix. The solution of the system of equations (32) may be written in matrix form as

$$\mathbf{y} = \tilde{\mathbf{T}}^{-1}[\mathbf{S} - \mu\mathbf{m}], \; j = 1, \ldots, J, \tag{34}$$

where $\mu\mathbf{m}$ denotes the $J-$vector with elements $\mu_i m_i$ and $\mathbf{S}$ denotes the vector of all polis sizes. This solution expresses the vector of real spending in terms of $\mathbf{S}$ and the vector of real coinage issues, $\mu\mathbf{m}$.

Taking as given the solution for polis $i$ spending (income) from (34), polis $i$ chooses $m_i$ so as to maximize (27), which may be rewritten as:

$$(1-g)[\ln Y_i - \ln P_i] + g \ln \Gamma_i = (1-g)\ln y_i - (1-g)\ln \tilde{P}_i + \ln \frac{w}{w_{+1}} + g \ln m_i - g \ln \mu_i,$$

where $\frac{w}{w_{+1}}$, the rate of wage deflation, may be obtained as follows in the case of a uniform monetary standard. With free flow of specie, all exchange rates are equal to 1 and equalization of wage rates, polis $i$ faces a monetary budget constraint:

$$S_i w_{i,+1} = S_i w_i + \mu_i M_i. \tag{35}$$

With equalization of nominal wage rates, equation (35) may be aggregated for the entire economy to yield:

$$w_{+1}\bar{S} = w\bar{S} + w\sum_i \mu_i m_i, \tag{36}$$

where $\bar{S} = \sum_i S_i$, and the $m_i$'s denote the real money supplies at the uniform wage standard. This condition underscores that seignorage is shared in the coinage union. Solving for the rate of inflation, we have:

$$\frac{w_{+1}}{w} = \frac{\bar{S}}{\bar{S} - \sum_i \mu_i m_i}. \tag{37}$$

Therefore, polis $i$ sets $m_i$ so as to maximize:

$$V_{i,trade,\,union} := (1-g)\ln y_i - (1-g)\ln \tilde{P}_i + (1-g)\ln\left[\frac{\bar{S} - \sum_i \mu_i m_i}{\bar{S}}\right] + g\ln m_i - g\ln \mu_i. \tag{38}$$

In order to focus on the role of local productivities and shipping costs, we ignore the presence of $\mu_i m_i$ in the term expressing the inflation rate, given $\ln\left[\frac{\bar{S}-\sum_i \mu_i m_i}{\bar{S}}\right]$. Indeed, with a large number of poleis, it is appropriate to take that term, an aggregate impact on polis welfare, as given when deriving first-order conditions in a Nash equilibrium setting. The resulting system of equations corresponding to first-order conditions with respect to the $m_i$'s is tractable. That is:

$$(1-g)\frac{1}{y_i}\frac{\partial y_i}{\partial m_i} + g\frac{1}{m_i} = 0. \tag{39}$$

In view of the dependence of the $y_i$'s on the $m_i$'s from (34), the system in matrix form yields the following solution for the vector of the $\mu_i m_i$'s:

$$\mu\mathbf{m} = \frac{g}{1-g}\left[\text{Diag}[\tilde{\mathbf{T}}^{-1}]\right]^{-1}\mathbf{y}, \tag{40}$$

where Diag$[\tilde{\mathbf{T}}^{-1}]$ denotes the matrix composed of the diagonal elements of matrix $[\tilde{\mathbf{T}}^{-1}]$. The solution for the vector $\mathbf{y}$ follows:

$$\left[(1-g)\tilde{\mathbf{T}} + g\left[\text{Diag}[\tilde{\mathbf{T}}^{-1}]\right]^{-1}\right]\mathbf{y} = (1-g)\mathbf{S}. \tag{41}$$

If $g$ is small, that is, the public good does not contribute substantially to individual utility, then no money is issued and the solution (41) simplifies to: $\mathbf{y} = \tilde{\mathbf{T}}^{-1}\mathbf{S}$. The intuition of this result is immediate, when seen as $\tilde{\mathbf{T}}\mathbf{y} = \mathbf{S}$, that supply of goods in each polis is equal to demand.

The resulting solution of (41) for the vector of real spending corresponds to a Nash equilibrium in the system of poleis when coinage issue is uncoordinated. As we discussed earlier, heeding Casella (1992), the outcome of uncoordinated coinage issue might be disadvantageous to a polis, relative to autarky. In such a case, in order to elicit participation in a coinage union, a system of utility weights may be designed, such that under a coordinated coinage issue, outcomes for all poleis of interest may above the value of autarky. In any case, the value of trade together with participation in a coinage union for each polis depends on all sizes, via $\mathbf{S}$, and the entire structure of shipping costs and productivities, via $[\tilde{\mathbf{T}}^{-1}]$ and Diag$[\tilde{\mathbf{T}}^{-1}]$, all of which are exogenous.

Therefore, participation by polis $i$ in trade and coinage union would be attractive if the optimum utility from (38) exceeds that of autarky from (29). That is:

$$(1-g)\ln y_i + \frac{1-g}{\sigma-1}\ln\sum_k\left(\frac{\tau_{ki}}{A_k}\right)^{1-\sigma} + (1-g)\ln\left[\frac{\bar{S}-\sum_i \mu_i m_i}{\bar{S}}\right] + g\ln m_i - g\ln\mu_i$$

$$\geq (1-g)\ln A_i + g\ln S_i, \tag{42}$$

where $y_i$ and $m_i$ are given, respectively, from the solving (41) and (40) above. These conditions involve all parameters, that is all sizes, productivities and shipping costs. Notably, all productivities and shipping costs enter via the matrix of parameters $\tilde{\mathbf{T}}$. *Cet. par.,* from comparing $\frac{1}{\sigma-1}\ln\sum_k\left(\frac{\tau_{ki}}{A_k}\right)^{1-\sigma}$ with $A_i$, the smaller are the shipping costs and the larger the productivities the more attractive is trade and participation in a coinage union.

If the actual sizes of poleis are not known, then we can make progress by assuming spatial equilibrium, that is, equilibrium utility is equalized across all poleis, and labor supply is infinitely elastic from the perspective of every site. For a full development along those we can work in like manner to Allen and Arkolakis (2014) and express demands, as in (30) in terms of utility. We may do that by first solving for the optimal value of $\Gamma_i$, substitute in for the price index $P_j$ in terms of utility and impose spatial equilibrium. Because of the presence of $\Gamma_i$, the derivations are more involved then in *ibid.* However, we may simplify by imposing consistency and setting $\mathbf{y}=\mathbf{S}$ in (41). Therefore, sizes are determined up to scale from the unique right Perron-Frobenius eigenvector of the positive matrix on the l.h.s. of (41), that are associated with the maximal eigenvalue of

$$\mathbf{T}^* := \left[(1-g)\tilde{\mathbf{T}} + g\left[\mathrm{Diag}[\tilde{\mathbf{T}}^{-1}]\right]^{-1}\right]. \tag{43}$$

Returning to (42), we recall the comparison between the utility from trade and coinage union vs. that from autarky, and note that the solutions for $y_i$, from (41), and for $m_i$, from (40), involve the full complement of geographic and productivity variables as well as the sizes of all poleis. Thus, network centrality is an attractive empirical proxy.

## 6.2 An Example with Two Poleis

Let us consider an example with two poleis, with polis $i = 1$, being a potential coinage hegemon in a coinage union with polis $i = 2 : \mu_2 > \mu_1 = 1$. In view of (38), Polis 1 would seek to maximize a weighted sum of the utilities of the two poleis,

$$V_{1,\,hegemon} := \phi_1 V_{1,trade,\,union} + \phi_2 V_{2,trade,\,union},$$

where the relative weights sum up to 1: $\phi_1 + \phi_2 = 1$. In view of (41) and (43), let us denote the rows of $[\mathbf{T}^*]^{-1}$ by $[\mathbf{T}^*]^{-1}_{(1)}, [\mathbf{T}^*]^{-1}_{(2)}$. The first order conditions for the maximization of $V_{1,\,hegemon}$ are:

$$\phi_1 \frac{g}{m_1} - \phi_1(1-g)[\mathbf{T}^*]^{-1}_{(1,1)} \frac{\mu_1}{y_1} = \phi_1(1-g)[\mathbf{T}^*]^{-1}_{(2,1)} \frac{\mu_1}{y_2} + (1-g)\frac{\mu_1}{\bar{S} - \mu_1 m_1 - \mu_2 m_2}; \qquad (44)$$

$$\phi_2 \frac{g}{m_2} - \phi_2(1-g)[\mathbf{T}^*]^{-1}_{(2,2)} \frac{\mu_2}{y_2} = \phi_2(1-g)[\mathbf{T}^*]^{-1}_{(1,2)} \frac{\mu_2}{y_1} + (1-g)\frac{\mu_2}{\bar{S} - \mu_1 m_1 - \mu_2 m_2}, \qquad (45)$$

with $(y_1, y_2)$ given by (34), and rewritten here as:

$$y_1 = [\mathbf{T}^*]^{-1}_{(1,1)}(S_1 - \mu_1 m_1) + [\mathbf{T}^*]^{-1}_{(1,2)}(S_2 - \mu_2 m_2), y_2 = [\mathbf{T}^*]^{-1}_{(2,1)}(S_1 - \mu_1 m_1) + [\mathbf{T}^*]^{-1}_{(2,2)}(S_2 - \mu_2 m_2).$$

The optimal values of the real monies for the coinage union, $(m_1^*, m_2^*)$ no longer satisfy (39) and thus (40), the solutions for the polis-specific optimal values of real money, which ignore the impact of each money supply on the global inflation rate. Instead, the coinage hegemon internalizes this effect, which is represented by the last term in the r.h.s. of (44) and (45). Since the r.h.s.'s of those equations are positive, so should their l.h.s.'s be, which implies that $(m_1^*, m_2^*)$ must be less than the respective polis-specific optimal solutions, at which the l.h.s. of (44) and (45) are equal to 0.[45] For voluntary participation in the coinage union by polis 2, its utility outcome must exceed that associated with autarky, given by $V_{i,aut,nocoinage}$,

[45] This is identical to the result obtained by Casella (1992), namely that inflation in an uncoordinated Nash equilibrium would be greater than in a coordinated one.

from (10).

To see the impact of the higher coinage costs for polis 2, let us subtract equation (45) from equation (44):

$$\phi_1 \left[ \frac{g}{m_1} - (1-g)[\mathbf{T}^*]^{-1}_{(1,1)} \frac{\mu_1}{y_1} \right] - \phi_2 \left[ \frac{g}{m_2} - (1-g)[\mathbf{T}^*]^{-1}_{(2,2)} \frac{\mu_2}{y_2} \right]$$

$$= (1-g) \left[ \phi_1 [\mathbf{T}^*]^{-1}_{(2,1)} \frac{\mu_1}{y_2} - \phi_2 [\mathbf{T}^*]^{-1}_{(1,2)} \frac{\mu_2}{y_1} \right] + (1-g) \frac{1}{\bar{S} - \mu_1 m_1 - \mu_2 m_2} [\mu_1 - \mu_2]. \tag{46}$$

## 6.3 Geopolitical Considerations for Coinage Unions

Taking a geopolitical view of coinage unions in that era, namely that they were meant to maintain influence over member poleis, we see that the larger is $\mu_2$ relative to $\mu_1$, the larger weight $\phi_2$ polis 1 must assign to the welfare of polis 2. So, if those costs increase with distance of polis 2 from polis 1, there exists a threshold beyond which a coinage union would no longer be attractive to polis 1, the hegemon, whose advantage over coinage issue would be depleted and its own welfare decreased. In view of the fact there are a few poleis in the area of our study with coinage issue advantage, dependence of coinage issue is generated on the distances of a less advantaged polis from more advantaged ones. In other words, the options that a polis suffering from a coinage minting disadvantage may have by exploring coinage unions with other poleis work to boost its reservation utility over and above autarky. Therefore, earlier coinage issue may be facilitated by proximity to more advantaged poleis, but this effect is weakened by distance, while the likelihood of independent coinage is strenghtened by distance from other poleis with coinage advantage. These considerations apply more generally to the behavior of poleis that are not necessarily linked by coinage unions or alliance considerations.

# 7 APPENDIX B: Adoption Curves

Figure 11 is the adoption curve for scripts based on raw data. The vertical axis is the cumulative number of poleis adopting a script, and the horizontal axis is the adoption date, ranging from 725 BCE to 416 BCE.

We are, however, reluctant to draw undue conclusions from Figure 11. A first limitation is due to the fact that the script adoption process in effect ends by the time Athens officially adopts the Ionian script in 403-402 BCE. Thus we argue that because of the dominant position of Athens, the "natural" adoption process ceases. A second limitation comes from the nature of our scripts data base, Poinikastas, in which the unit of observation is scripts. It includes both local scripts (i.e., scripts associated with a single polis) as well as regional scripts. The latter are somewhat problematic for the conceptualization of the adoption process and therefore the adoption curve, as well. Whereas for regional scripts we do know their earliest date of attestation, we do not know when each polis in the respective region actually did adopt the regional script. We therefore assign the earliest date of attestation for the regional script to all poleis within the region, while in reality some poleis might have adopted at later times. The regional scripts are the cause of steep "jumps" in the script adoption curve. A third limitation stems from the fact that there exist a few scripts in Poinikastas that we have been unable to matched to our poleis database and are thus ignored.

Figure 12 reports the adoption curve for coinage. Our observations for coinage issue by poleis lie between 610 BCE and 280 BCE. Like with scripts, the adoption process for coinage does not reflect entirely voluntary decisions by poleis though for different reasons. Athens, the coinage hegemon the Delian League, made its own coinage mandatory on the League members, requiring them after some point to turn in their coinage to the Athenian mint in exchange for Athenian coinage.

Since we have two sources of coinage issue dates, we draw two separate adoption curves: Figure 12a is based on "exact" dates attested, while Figure 12b is based on an augmented sample that also include poleis for which information is attested in terms of centuries, within which coinage was issued. We therefore compute the numbers of coinage issues in each century. The vagaries of the archaeological record are responsible for the differences, including the period of observation. E.g., we only have one observation in the 3rd century BCE, that is, 280 BCE. The adoption curve before the 3rd century BCE is plotted with solid line, with the observation at 280 BCE being added with a dashed line. The adoption curve is shown only up to the 4th century BCE. Note that while the 7th century BCE is marked on the graph, the graph could be misleading from 7th century to the 6th century BCE, since the adoption process did not start from the beginning of 7th century BCE. Actually, there is also only one observation of coinage in the 7th century BCE, at 610 BCE, which marks the beginning of the coinage era in the Hellenic world in our data. The exact numbers of coinage issues by century, based on our data, is: 1 in 7th century BCE, 94 in 6th century BCE, 144 in 5 century BCE, 197 in 4th century BCE, and 1 in 3rd century BCE.

Comparison of Figure 11 and Figure 12a hints that whereas script adoptions steadily accelerate, coinage issues appear to be closer to a sigmoid pattern.

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Figure 1: Kirchhoff Map of Epichoric Scripts


Distribution of alphabet types, after Kirchhoff (1867).

Southern: "green;" Western: "red;" Eastern: "light blue;" classic Ionian: “dark blue.”

https://en.wikipedia.org/wiki/Archaic_Greek_alphabets

After a map in E. Voutiras (2001), “The introduction of the alphabet.” In: Anastasios-Phoivos Christidēs (ed.) *A history of Ancient Greek: from the beginnings to late antiquity*, p.270f., which in turn purports to reproduce the contents of the map in Kirchhoff (1867), *Studien zur Geschichte des griechischen Alphabets*; together with some additional data from Jeffery (1961), *The Local Scripts of Archaic Greece*.

Figure 2: Poleis around the Mediterranean

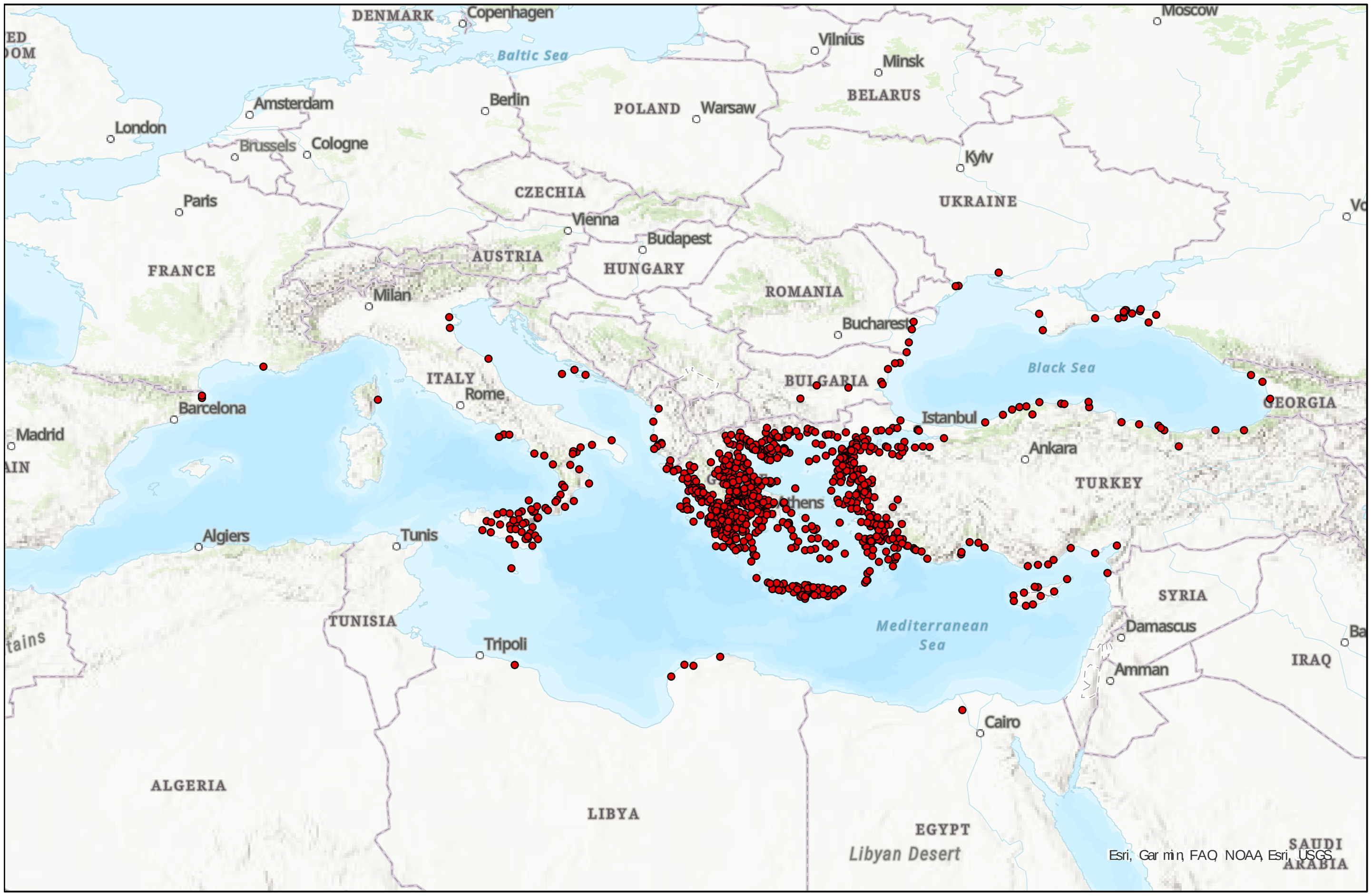
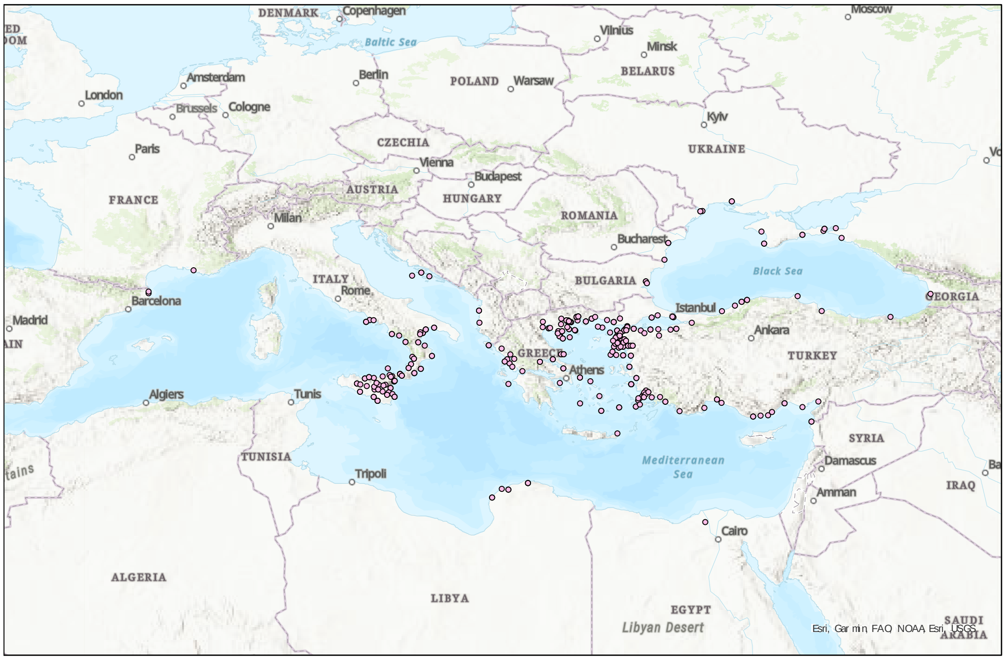


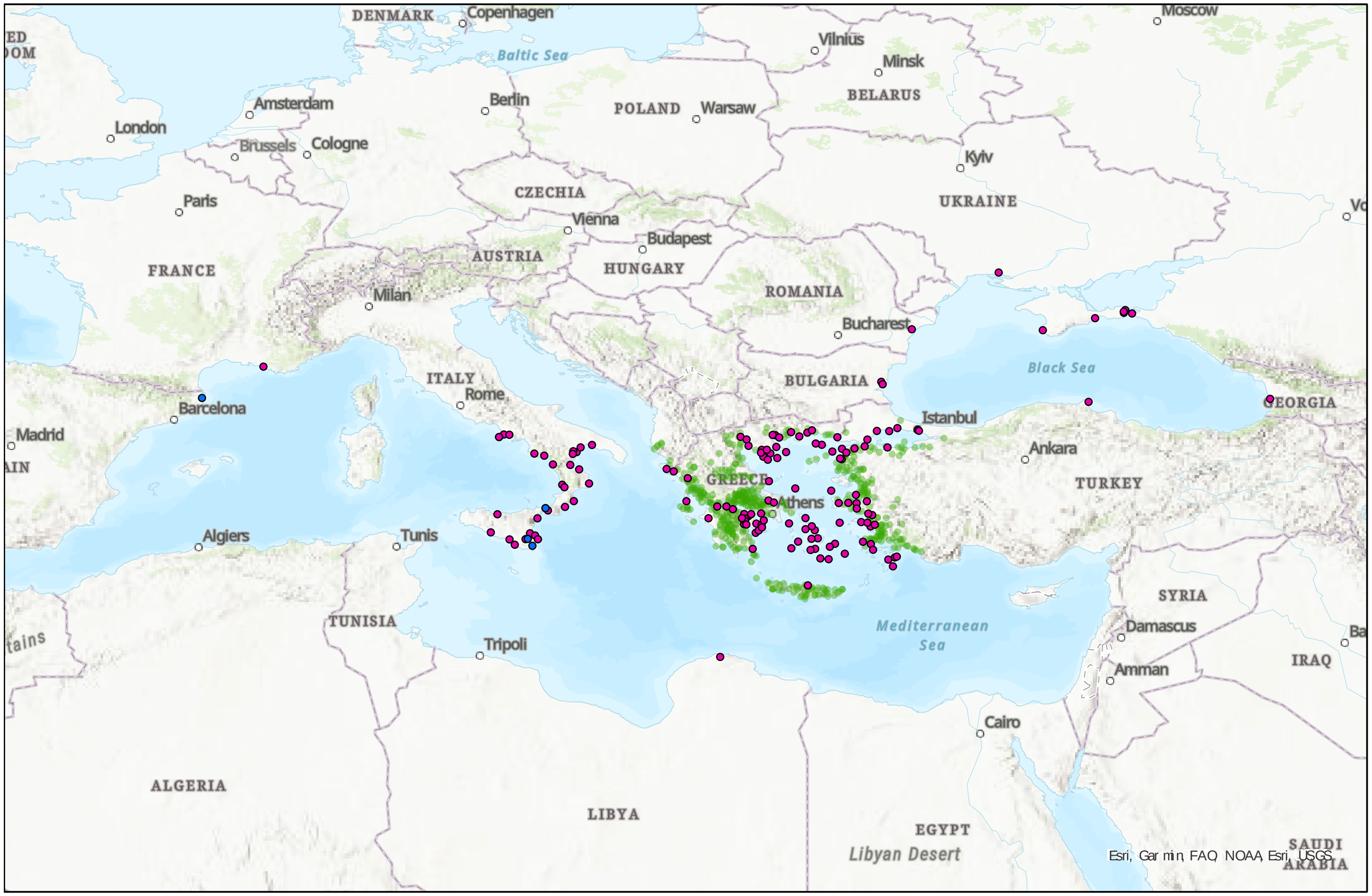
Figure 3: Poleis with Coinage




(a) Poleis with precise coinage dates


(b) Poleis with imprecise coinage dates only

Figure 4: Poleis with scripts




*Notes:* Red dots denote polis with local scripts, green dots denote polis with regional scripts, and blue dots polis with colonizer's scripts (dates are cut off at 415 BCE).

Figure 5: Histograms for Dates of Script Adoption and Coinage

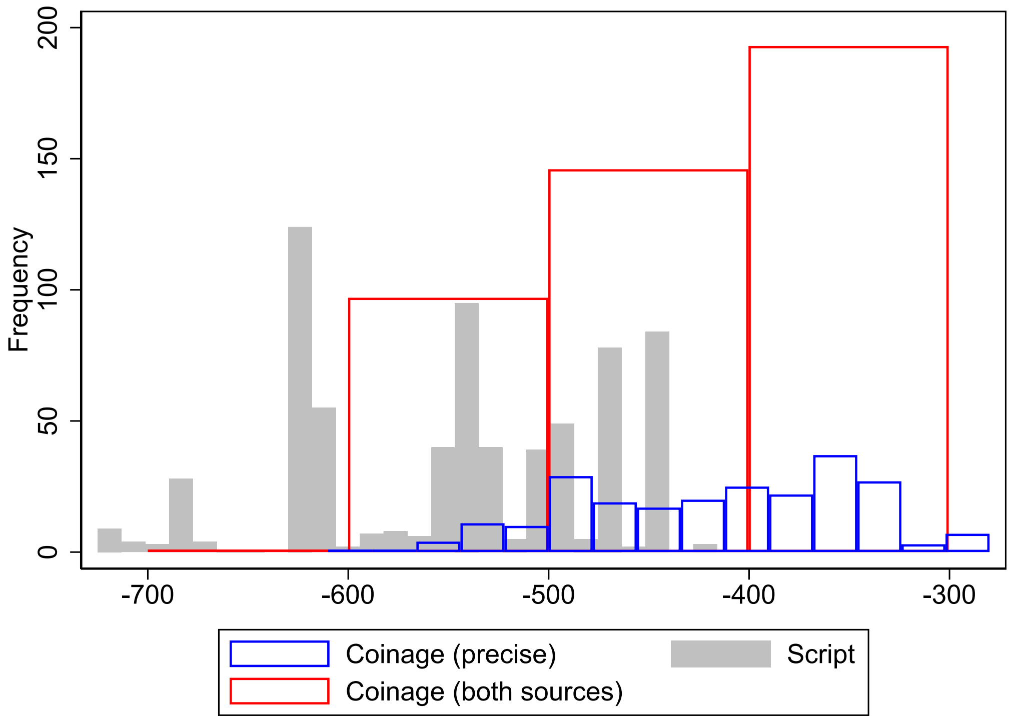
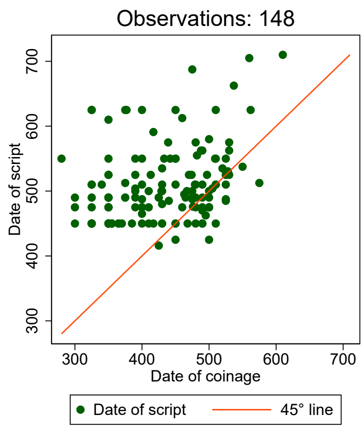
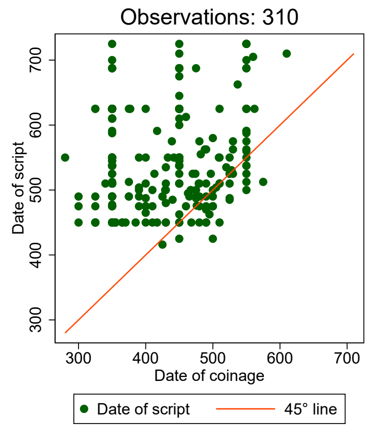


Figure 6: Dates of Scripts and Coinage



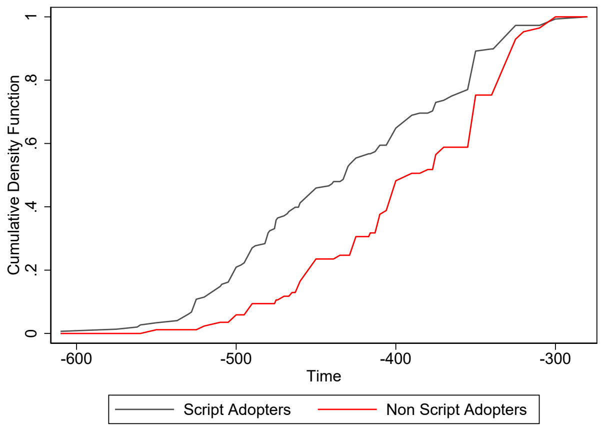

(a) Poleis with attested coinage issue year



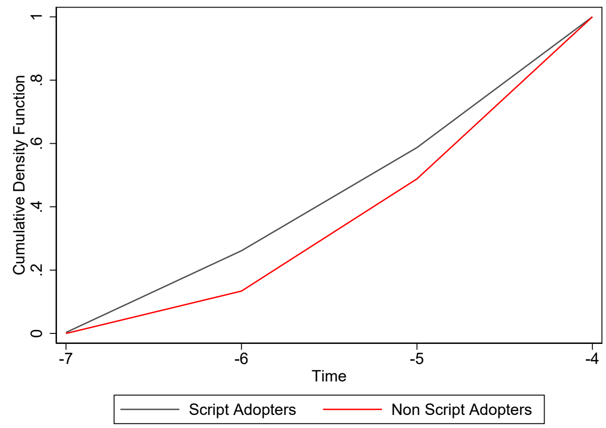

(b) All poleis with coinage issues, attested by year of century

*Notes:* In panel b, for the imprecise coinage dates which is originally given in century, we assume the coinage date to be the middle of each century.

Figure 7: Cumulative Distribution Functions of Coinage by Date, by whether a Script is ever Adopted



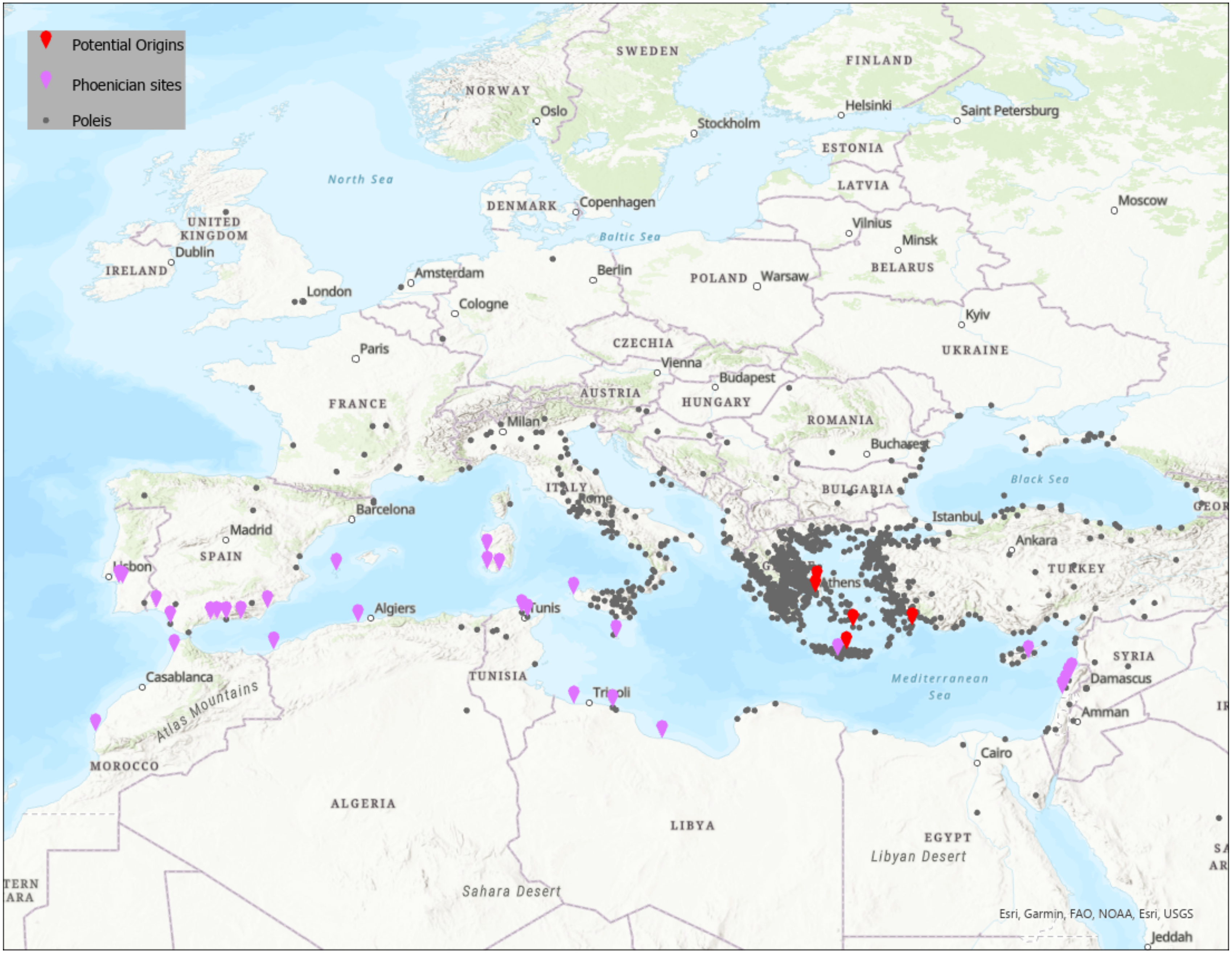

(a) Poleis with attested coinage issue year

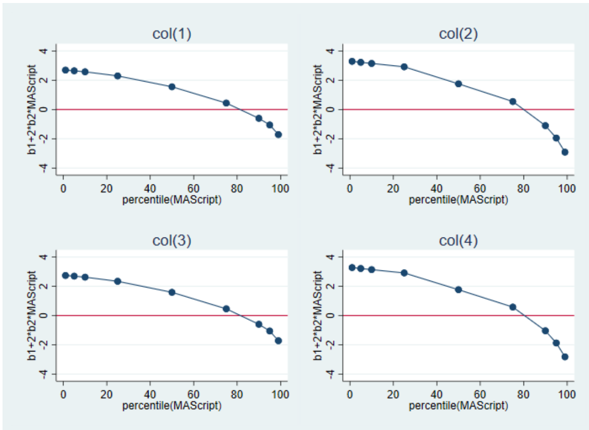



(b) All poleis with coinage issues, by century

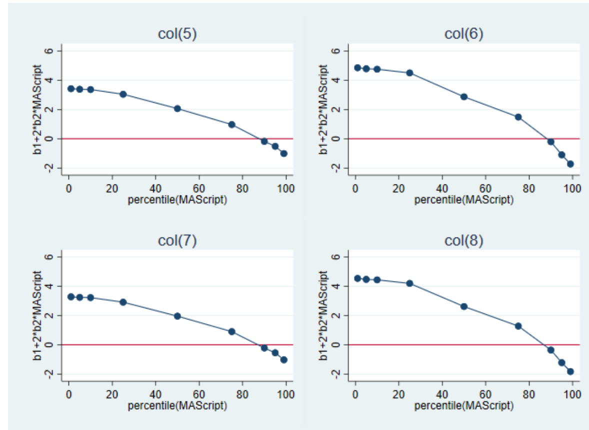
*Notes:* In panel b, the attested coinage issue date is aggregated to the century level.

Figure 8: Location of Phoenician Colonies around the Mediterranean



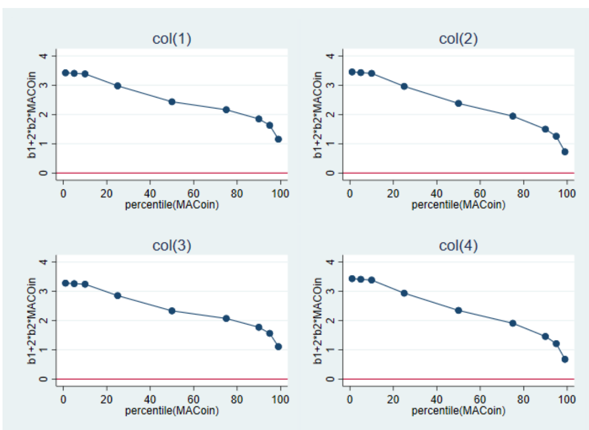



(a) Col (1) - (4)

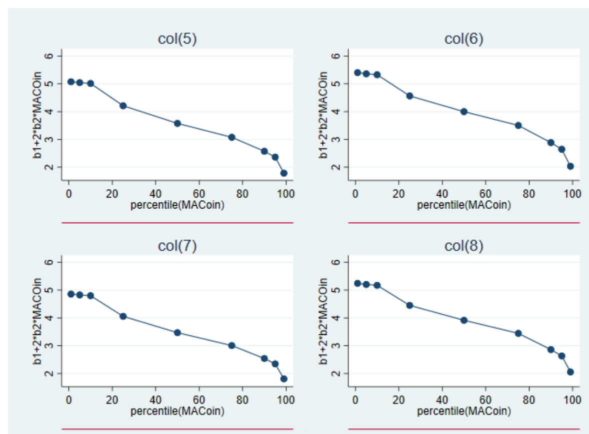



(b) Col (5) - (8)

Figure 9: Imputed Nonlinear Effects of MAScript (Based on Table 11)




(a) Col (1) - (4)




(b) Col (5) - (8)

Figure 10: Imputed Nonlinear Effects of MACoin (Based on Table 13)

Table 1: Tabulate, coinage and script

| | Script | | |
|---|---|---|---|
| | 0 | 1 | Total |
| Coin=0 | 397 | 382 | 779 |
| Coin=1 | 127 | 310 | 437 |
| Total | 524 | 692 | 1216 |

Table 2: Observation Counts by Script Adoption and Coinage Issue groups

| | (1) |
|---|---|
| | count |
| no_script_no_coin | 397 |
| no_script_with_coin | 85 |
| with_script_no_coin | 382 |
| script_earlier_than_coin | 116 |
| script_later_than_coin | 23 |
| script_sametime_coin | 9 |
| coin_no_exact_date | 204 |

Table 3: Probit Regression: Coinage Indicator against Script Indicator

| | (1)<br>Coin | (2)<br>Coin | (3)<br>Coin | (4)<br>Coin | (5)<br>Coin |
|---|---|---|---|---|---|
| script | 0.566*** | 0.592*** | 0.651*** | 0.381*** | 0.492*** |
| | (0.0767) | (0.0944) | (0.0996) | (0.107) | (0.144) |
| Constant | -0.697*** | -1.584*** | -2.422*** | -1.566 | -2.520* |
| | (0.0600) | (0.594) | (0.935) | (1.112) | (1.451) |
| Geo vars | | X | X | X | X |
| Centrality | | | X | X | X |
| Membership | | | | X | X |
| size | | | | | X |
| Observations | 1215 | 1065 | 1065 | 890 | 631 |
| Pseudo-R2 | 0.035 | 0.096 | 0.102 | 0.069 | 0.236 |
| N(Coin=1) | 437 | 424 | 424 | 424 | 334 |

Notes: Probit regression for coinage against script adoption indicator. Geographical variables here include ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability. Centrality variables include stochastic right eigenvector, authority, and hub centrality based on the poleis sample. Membership includes Delian and Koinon (Federation) memberships. Robust standard error in parentheses. $^{*}$ $p < 0.1$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$

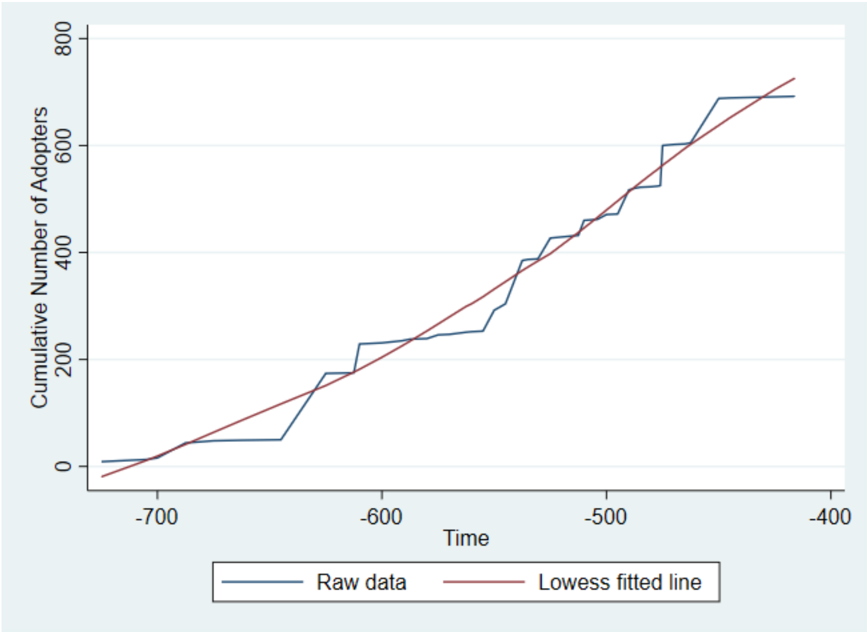
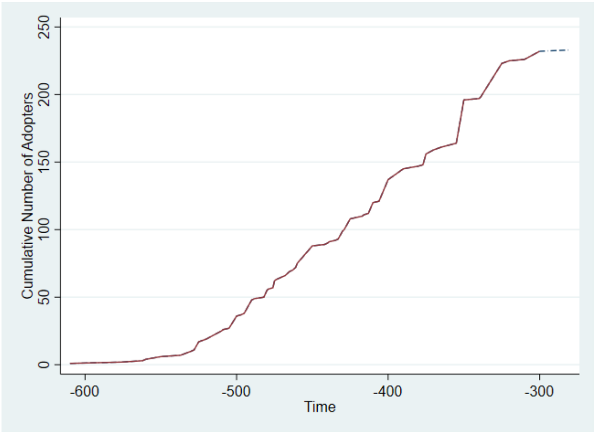
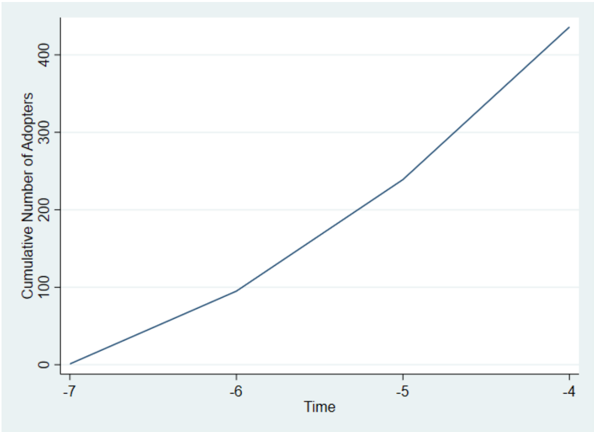



Figure 11: Adoption Curve for Scripts




(a) Precise Date




(b) Precise and Imprecise Date

Figure 12: Adoption Curve for Coins

Table 4: OLS Regression: Coinage Issue Date against Script Indicator

| | (1)<br>Date | (2)<br>Date | (3)<br>Date | (4)<br>Date | (5)<br>Date |
|---|---|---|---|---|---|
| script | -39.29*** | -48.16*** | -53.41*** | -50.56*** | -39.62*** |
| | (8.797) | (9.271) | (10.35) | (10.53) | (12.40) |
| Constant | -390.8*** | -217.2*** | -293.2*** | -329.5*** | -308.0** |
| | (6.529) | (56.29) | (109.5) | (114.3) | (136.0) |
| Geo vars | | X | X | X | X |
| Centrality | | | X | X | X |
| Membership | | | | X | X |
| size | | | | | X |
| Observations | 233 | 223 | 223 | 223 | 155 |
| R2-adj | 0.069 | 0.210 | 0.206 | 0.217 | 0.250 |

Notes: OLS regression for date of coinage against script adoption indicator. Smaller coefficients imply earlier coinage issues. Geographical variables include ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability. Centrality variables include stochastic right eigenvector, authority, and hub centrality based on the poleis sample. Membership includes Delian and Koinon (Federation) memberships.

Robust standard error in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Bivariate Probit: Script Adoption and Coinage Issue Indicators

| | Stochastic centrality | | | Nonstochastic centrality | | | |
|---|---|---|---|---|---|---|---|
| | (1) RightEV | (2) Auth | (3) Hub | (4) RightEV | (5) LeftEV | (6) Auth | (7) Hub |
| script | | | | | | | |
| centrality | -166.0 | 908.1* | 73.95 | 230.5** | 428.9*** | 637.1*** | 377.6*** |
| | (107.5) | (504.7) | (164.0) | (113.9) | (158.1) | (160.5) | (128.4) |
| Constant | -1.302 | -0.973 | -0.666 | -0.287 | -2.074** | -2.056** | -0.472 |
| | (0.842) | (0.772) | (0.820) | (0.801) | (0.917) | (0.860) | (0.771) |
| coin | | | | | | | |
| centrality | -236.8** | -1829.2*** | -549.4*** | -462.0*** | 129.8 | -144.4 | -476.4*** |
| | (105.2) | (515.2) | (160.4) | (111.5) | (127.1) | (138.4) | (125.9) |
| Constant | -2.664*** | -1.675** | -2.987*** | -3.100*** | -2.258*** | -1.548** | -2.413*** |
| | (0.820) | (0.736) | (0.808) | (0.794) | (0.843) | (0.776) | (0.737) |
| / | | | | | | | |
| athrho | 0.169*** | 0.192*** | 0.180*** | 0.197*** | 0.172*** | 0.191*** | 0.204*** |
| | (0.0604) | (0.0610) | (0.0607) | (0.0612) | (0.0609) | (0.0616) | (0.0616) |
| Observations | 890 | 890 | 890 | 890 | 890 | 890 | 890 |

Robust standard error in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: Control variables include ruggedness, malaria index, temperature, precipitation, elevation, crop suitabilities, Koinon (Federation) and Delian League Membership, and crops suitabilities are not shown to save space.

Table 6: Seemingly Unrelated Regressions: Dates of Script Adoption and Coinage Issue

| | Stochastic centrality | | | Nonstochastic centrality | | | |
|---|---|---|---|---|---|---|---|
| | (1) RightEV | (2) Auth | (3) Hub | (4) RightEV | (5) LeftEV | (6) Auth | (7) Hub |
| script_date | | | | | | | |
| centrality | -25142.0*** | -89436.7** | -27558.1** | -21036.9** | -8292.2 | -5324.1 | -13778.8 |
| | (8869.5) | (41044.5) | (13053.3) | (8958.4) | (10742.0) | (12686.8) | (11306.2) |
| Constant | -437.3*** | -349.9*** | -409.8*** | -416.1*** | -315.5*** | -334.4*** | -367.0*** |
| | (71.69) | (64.30) | (71.18) | (70.90) | (75.40) | (69.82) | (67.00) |
| coin_date | | | | | | | |
| centrality | 254.0** | 1946.9*** | 524.6*** | 335.9*** | 460.1*** | 658.4*** | 630.4*** |
| | (106.0) | (480.0) | (153.7) | (106.0) | (125.4) | (146.4) | (130.1) |
| Constant | -2.180** | -3.011*** | -1.882** | -1.980** | -4.767*** | -4.465*** | -2.119*** |
| | (0.857) | (0.752) | (0.838) | (0.839) | (0.880) | (0.806) | (0.771) |
| Observations | 307 | 307 | 307 | 307 | 307 | 307 | 307 |

Standard error in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: Control variables include ruggedness, malaria index, temperature, precipitation, elevation, crop suitabilities, Koinon (Federation) and Delian League Membership, and crops suitability are not shown to save space.

Table 7: Seemingly Unrelated Regressions (poleis with imprecise coinage date dropped)

| | Stochastic centrality | | | Nonstochastic centrality | | | |
|---|---|---|---|---|---|---|---|
| | (1) RightEV | (2) Auth | (3) Hub | (4) RightEV | (5) LeftEV | (6) Auth | (7) Hub |
| script_date | | | | | | | |
| centrality | -5405.8 | -68859.8 | -3907.6 | 439.3 | 14204.7 | 11646.4 | 12754.6 |
| | (11943.6) | (52940.8) | (17854.8) | (11705.9) | (12403.4) | (15019.4) | (14328.0) |
| Constant | -543.1*** | -517.3*** | -537.0*** | -531.1*** | -570.0*** | -548.0*** | -520.1*** |
| | (71.37) | (67.58) | (70.81) | (71.06) | (74.54) | (69.99) | (68.15) |
| coin_date | | | | | | | |
| centrality | 17606.5 | 97744.6 | 36528.3* | 25619.6* | 51378.6*** | 68807.3*** | 58531.6*** |
| | (14605.7) | (64889.8) | (21721.7) | (14218.8) | (14698.2) | (17584.1) | (16965.9) |
| Constant | -199.6** | -256.8*** | -189.1** | -184.2** | -373.6*** | -330.5*** | -181.5** |
| | (87.28) | (82.84) | (86.15) | (86.31) | (88.33) | (81.95) | (80.70) |
| Observations | 146 | 146 | 146 | 146 | 146 | 146 | 146 |

Standard error in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: Control variables include ruggedness, malaria index, temperature, precipitation, elevation, crop suitabilities, Koinon (Federation) and Delian League Membership, and crops suitability are not shown to save space.

Table 8: Survival Analysis: Date of Script Adoption

| | Dependent var: survival time until adopting a script | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| MA: Phoenician Sites | 2.705** | 2.307* | 2.509** | 2.219* | 0.562 | 1.947 | 1.394 | 1.823 |
| | (1.206) | (1.197) | (1.223) | (1.188) | (1.170) | (1.274) | (1.239) | (1.265) |
| MA: Potential Origins | | -9.179*** | | -10.38*** | | -11.15*** | | -11.98*** |
| | | (2.482) | | (3.202) | | (2.527) | | (3.591) |
| Authority Centrality | -1033.6* | -1816.1*** | -370.0** | -809.5*** | -1395.7** | 258.0 | -486.2*** | 162.0 |
| | (619.4) | (660.5) | (173.0) | (215.7) | (602.6) | (627.3) | (173.3) | (228.0) |
| Hub Centrality | -163.6 | 1368.1* | -181.0 | 468.9** | -68.46 | -125.4 | -176.2 | -8.137 |
| | (547.8) | (703.0) | (138.1) | (233.5) | (543.6) | (534.2) | (138.1) | (149.0) |
| _cons | 8.592*** | 7.948*** | 9.005*** | 8.788*** | 8.264*** | 8.716*** | 8.783*** | 8.552*** |
| | (0.739) | (0.675) | (0.805) | (0.737) | (0.697) | (0.720) | (0.772) | (0.711) |
| lnsigma | -0.0224 | -0.0508 | -0.0259 | -0.0578 | -0.0190 | -0.0561 | -0.0236 | -0.0574 |
| | (0.0745) | (0.0725) | (0.0766) | (0.0725) | (0.0751) | (0.0762) | (0.0775) | (0.0754) |
| lntheta | -16.23*** | -16.91*** | -16.89*** | -17.51*** | -16.63*** | -16.71*** | -16.17*** | -16.39*** |
| | (0.125) | (0.177) | (0.128) | (0.264) | (0.124) | (0.194) | (0.131) | (0.260) |
| MA Direction | FROM | FROM | FROM | FROM | TO | TO | TO | TO |
| Centrality Sample | Segment | Segment | Poleis | Poleis | Segment | Segment | Poleis | Poleis |
| Elasticity: MA: Potential Origins | | -0.317 | | -0.358 | | -0.379 | | -0.407 |
| Elasticity: Authority Centrality | -0.161 | -0.283 | -0.163 | -0.357 | -0.217 | 0.040 | -0.214 | 0.071 |
| Elasticity: MA: Phoenician Colonies | 0.130 | 0.111 | 0.121 | 0.107 | 0.021 | 0.073 | 0.053 | 0.069 |
| Observations | 1065 | 1065 | 1065 | 1065 | 1065 | 1065 | 1065 | 1065 |
| chi-squared | 160.227 | 175.675 | 177.399 | 195.907 | 164.860 | 185.493 | 177.849 | 190.741 |
| log likelihood | -1120.720 | -1101.792 | -1116.419 | -1095.995 | -1123.406 | -1094.990 | -1118.316 | -1094.602 |

Notes: Survival analysis for script adoption. All poleis are assumed to adopt a script at 400 BCE (censored at 400 BCE). Geographical variables include ruggedness, malaria index, temperature, precipitation, elevation, and crop (barley, millet, summer wheat and winter wheat) suitability are not shown to save space. Centralities are non-stochastic centralities.
Elasticity is computed as coefficient times standard deviation.
Robust standard error in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 9: Survival Analysis: Date of Coinage Issue

| | Dependent var: survival time until issuing a coin | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| MA: Origins/Mines | -0.0242 | -0.974 | -3.593** | -3.657** | -2.544** | -3.739*** | -4.000*** | -4.536*** |
| | (0.736) | (0.980) | (1.506) | (1.649) | (1.039) | (1.401) | (1.276) | (1.471) |
| Authority Centrality | 624.2 | -352.2 | 3.744 | -217.5 | 813.9 | -27.46 | 216.5 | 64.35 |
| | (574.9) | (636.5) | (196.1) | (178.0) | (589.7) | (655.9) | (237.0) | (236.0) |
| Hub Centrality | 1703.8*** | 1084.7 | 1104.3*** | 764.6*** | 1663.0*** | 935.9 | 725.3*** | 356.6** |
| | (604.2) | (849.3) | (217.4) | (247.7) | (542.5) | (635.7) | (166.7) | (178.2) |
| Federal State Membership | 0.270** | | 0.154 | | 0.244* | | 0.0950 | |
| | (0.129) | | (0.121) | | (0.133) | | (0.132) | |
| Delian League Membership | -0.640*** | | -0.607*** | | -0.569*** | | -0.594*** | |
| | (0.104) | | (0.111) | | (0.103) | | (0.115) | |
| _cons | 8.401*** | 7.903*** | 8.814*** | 8.307*** | 8.905*** | 8.469*** | 9.070*** | 8.513*** |
| | (0.631) | (0.558) | (0.713) | (0.636) | (0.692) | (0.641) | (0.699) | (0.641) |
| lnsigma | -0.392*** | -0.428** | -0.430*** | -0.367** | -0.335*** | -0.324* | -0.423*** | -0.364** |
| | (0.112) | (0.169) | (0.128) | (0.150) | (0.111) | (0.189) | (0.131) | (0.170) |
| lntheta | -0.138 | 0.927* | -0.0640 | 0.618 | -0.668 | 0.435 | -0.134 | 0.585 |
| | (0.626) | (0.547) | (0.668) | (0.596) | (0.967) | (0.927) | (0.756) | (0.726) |
| MA Direction | FROM | FROM | FROM | FROM | TO | TO | TO | TO |
| Centrality Sample | Segment | Segment | Poleis | Poleis | Segment | Segment | Poleis | Poleis |
| Elasticity: MA: Origins/Mines | -0.001 | -0.058 | -0.221 | -0.217 | -0.148 | -0.206 | -0.233 | -0.250 |
| Elasticity: Hub Centrality | 0.303 | 0.191 | 0.551 | 0.402 | 0.296 | 0.165 | 0.362 | 0.188 |
| Observations | 689 | 863 | 689 | 863 | 689 | 863 | 689 | 863 |
| chi-squared | 148.396 | 121.723 | 151.351 | 115.307 | 151.826 | 122.650 | 149.592 | 116.992 |
| log likelihood | -461.495 | -534.850 | -452.018 | -529.860 | -457.913 | -529.634 | -449.716 | -526.631 |

Notes: Survival analysis for Coinage adoption. All poleis are assumed to have a coin at 250 BCE (censored at 250 BCE). Geographical variables include ruggedness, malaria index, temperature, precipitation, elevation, and crop (barley, millet, summer wheat and winter wheat) suitability are not shown to save space. Centralities are non-stochastic centralities.

Robust standard error in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 10: Script Pseudo Panel

| | (1) script | (2) script | (3) script | (4) script | (5) script | (6) script | (7) script | (8) script |
|---|---|---|---|---|---|---|---|---|
| 1-MAScript | 0.966*** | 2.154*** | 0.985*** | 2.111*** | 0.638*** | 1.199*** | 0.672*** | 1.277*** |
| | (0.172) | (0.289) | (0.170) | (0.288) | (0.164) | (0.306) | (0.164) | (0.304) |
| MAScript(1-MAScript) | 3.164*** | 4.289*** | 3.356*** | 4.348*** | 4.213*** | 5.561*** | 4.110*** | 5.201*** |
| | (0.509) | (0.828) | (0.516) | (0.832) | (0.545) | (0.897) | (0.528) | (0.879) |
| size | | 0.00347 | | 0.00563 | | 0.00881 | | 0.0110 |
| | | (0.00704) | | (0.00684) | | (0.00716) | | (0.00708) |
| _cons | -0.942*** | -2.410*** | -1.036*** | -2.497*** | -0.707*** | -1.407*** | -0.796*** | -1.617*** |
| | (0.185) | (0.340) | (0.184) | (0.347) | (0.189) | (0.368) | (0.188) | (0.377) |
| Period FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| MA Direction | FROM | FROM | FROM | FROM | TO | TO | TO | TO |
| Centrality Sample | Segment | Segment | Poleis | Poleis | Segment | Segment | Poleis | Poleis |
| Observations | 3870 | 1952 | 3870 | 1952 | 3870 | 1952 | 3870 | 1952 |
| R2-adj | 0.091 | 0.090 | 0.098 | 0.092 | 0.096 | 0.085 | 0.101 | 0.086 |

Notes: Pseudo panel analysis for script adoption. Geographical variables including ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability are not shown to save space.

Robust standard error in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 11: Pseudo Panel Analysis: Spatial Evolution of Script Adoption

| | (1)<br>script | (2)<br>script | (3)<br>script | (4)<br>script | (5)<br>script | (6)<br>script | (7)<br>script | (8)<br>script |
|---|---|---|---|---|---|---|---|---|
| MAScript | 2.198*** | 2.135*** | 2.371*** | 2.236*** | 3.575*** | 4.361*** | 3.438*** | 3.924*** |
| | (0.404) | (0.681) | (0.420) | (0.691) | (0.447) | (0.707) | (0.427) | (0.687) |
| $MAScript^2$ | -3.164*** | -4.289*** | -3.356*** | -4.348*** | -4.213*** | -5.561*** | -4.110*** | -5.201*** |
| | (0.509) | (0.828) | (0.516) | (0.832) | (0.545) | (0.897) | (0.528) | (0.879) |
| size | | 0.00347 | | 0.00563 | | 0.00881 | | 0.0110 |
| | | (0.00704) | | (0.00684) | | (0.00716) | | (0.00708) |
| _cons | 0.0247 | -0.256* | -0.0505 | -0.386** | -0.0688 | -0.207 | -0.123* | -0.340** |
| | (0.0643) | (0.146) | (0.0638) | (0.157) | (0.0677) | (0.148) | (0.0670) | (0.160) |
| Period FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| MA Direction | FROM | FROM | FROM | FROM | TO | TO | TO | TO |
| Centrality Sample | Segment | Segment | Poleis | Poleis | Segment | Segment | Poleis | Poleis |
| Mean(MAScript) | 0.236 | 0.219 | 0.236 | 0.219 | 0.266 | 0.255 | 0.266 | 0.255 |
| Mean(Script) | 0.149 | 0.213 | 0.149 | 0.213 | 0.149 | 0.213 | 0.149 | 0.213 |
| Observations | 3870 | 1952 | 3870 | 1952 | 3870 | 1952 | 3870 | 1952 |
| R2-adj | 0.091 | 0.090 | 0.098 | 0.092 | 0.096 | 0.085 | 0.101 | 0.086 |

Notes: Pseudo panel analysis for script adoption. Geographical variables include ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability are not shown to save space.

Robust standard error in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 12: Pseudo Panel Analysis: Spatial Evolution of Coinage Issue

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| | coin | coin | coin | coin | coin | coin | coin | coin |
| 1-MACoin | 8.796*** | 15.23 | 8.243*** | 13.75 | 17.13** | 16.67 | 17.17** | 16.23 |
| | (1.876) | (14.64) | (1.801) | (14.34) | (7.047) | (12.89) | (7.001) | (13.10) |
| MACoin(1-MACoin) | 12.21*** | 19.34 | 11.47*** | 17.55 | 22.36*** | 22.40 | 22.37*** | 21.82 |
| | (2.284) | (16.51) | (2.191) | (16.14) | (7.851) | (14.42) | (7.807) | (14.64) |
| size | | 0.0493*** | | 0.0495*** | | 0.0479*** | | 0.0483*** |
| | | (0.00713) | | (0.00705) | | (0.00718) | | (0.00708) |
| _cons | -8.856*** | -15.35 | -8.356*** | -13.96 | -17.27** | -16.88 | -17.37** | -16.54 |
| | (1.888) | (14.69) | (1.815) | (14.40) | (7.065) | (12.95) | (7.020) | (13.17) |
| Period FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| MA Direction | FROM | FROM | FROM | FROM | TO | TO | TO | TO |
| Centrality Sample | Segment | Segment | Poleis | Poleis | Segment | Segment | Poleis | Poleis |
| Observations | 3938 | 1987 | 3938 | 1987 | 3938 | 1987 | 3938 | 1987 |
| R2-adj | 0.030 | 0.102 | 0.031 | 0.102 | 0.037 | 0.110 | 0.039 | 0.111 |

Notes: Pseudo panel analysis for coinage. Poleis with imprecise coinage date only are dropped. Geographical variables include ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability are not shown to save space. Robust standard error in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 13: Pseudo Panel Analysis: Spatial Evolution of Coinage Issue

| | (1) coin | (2) coin | (3) coin | (4) coin | (5) coin | (6) coin | (7) coin | (8) coin |
|---|---|---|---|---|---|---|---|---|
| MACoin | 3.416*** | 4.107** | 3.224*** | 3.803** | 5.227*** | 5.724*** | 5.196*** | 5.590*** |
| | (0.522) | (1.961) | (0.506) | (1.895) | (0.914) | (1.743) | (0.919) | (1.734) |
| MACoin$^2$ | -12.21*** | -19.34 | -11.47*** | -17.55 | -22.36*** | -22.40 | -22.37*** | -21.82 |
| | (2.284) | (16.51) | (2.191) | (16.14) | (7.851) | (14.42) | (7.807) | (14.64) |
| size | | 0.0493*** | | 0.0495*** | | 0.0479*** | | 0.0483*** |
| | | (0.00713) | | (0.00705) | | (0.00718) | | (0.00708) |
| _cons | -0.0600 | -0.116 | -0.113* | -0.207 | -0.135** | -0.212 | -0.199*** | -0.311* |
| | (0.0634) | (0.163) | (0.0665) | (0.185) | (0.0635) | (0.161) | (0.0677) | (0.183) |
| Period FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| MA Direction | FROM | FROM | FROM | FROM | TO | TO | TO | TO |
| Centrality Sample | Segment | Segment | Poleis | Poleis | Segment | Segment | Poleis | Poleis |
| Mean(MACoin) | 0.046 | 0.045 | 0.046 | 0.045 | 0.041 | 0.039 | 0.041 | 0.039 |
| Mean(Coin) | 0.044 | 0.060 | 0.044 | 0.060 | 0.044 | 0.060 | 0.044 | 0.060 |
| Observations | 3938 | 1987 | 3938 | 1987 | 3938 | 1987 | 3938 | 1987 |
| R2-adj | 0.030 | 0.102 | 0.031 | 0.102 | 0.037 | 0.110 | 0.039 | 0.111 |

Notes: Pseudo panel analysis for coinage. Poleis with imprecise coinage date only are dropped. Geographical variables include ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability are not shown to save space. Robust standard error in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$